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QUANTIFICATION OF THE EFFECTS OF VARIOUS LEVELS OF SEVERAL CRITICAL SHOT PEEN PROCESS VARIABLES ON WORKPIECE SURFACE INTEGRITY AND THE RESULTANT EFFECT ON WORKPIECE FATIGUE LIFE BEHAVIOR

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This technical report has been reviewed and is approved for publication.

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The purpose of this program is to acquire a statistical data base from which a mathematical model can be established to define the fatigue behavior of several materials that were prepared with various levels of shot peen process parameters. The objective of this model is to establish those shot peening process parameters that will produce optimum fatigue behavior in a variety of commonly used materials.

During the program, fatigue performance data was collected from 1148 specimens made from 11 materials. Shot peening parameters included variations in shot intensity, shot media and size, Almen saturation, broken particle content, impact angle, and initial specimen surface condition. The fatigue performance data indicated that an optimum fatigue life could be obtained with variations in intensity. Typically, relatively low levels of shot peening intensity produced the longest fatigue life and increased peening coverage and intensity reduced the life; in some cases, dramatic decreases in life occurred with increases in coverage.

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1.0 INTRODUCTION

This report covers Contract Number F33615-84-C-3229, "Quantification of the Effects of Various Levels of Several Critical Shot Peen Process Variables on Workpiece Surface Integrity and the Resultant Effect on Workpiece Fatigue Life Behavior." This contract is the continuation of a program with a previous contract, F33615-83-C-3252, "Development of a Mathematical Model for Predicting the Percentage Fatigue Life Increase Resulting from Shot Peened Components, Phase I," final report dated April, 1985. The previous contract report was published by the Air Force Wright Aeronautical Laboratories in April, 1985 (AFWAL-TR-84-3116). The program is funded through the Small Business Innovative Research (SBIR) grant program of the U.S. Department of Defense. This effort represents Phase II of the three-phase effort prescribed by the Federal Small Business Innovative Research Act (SBIR) of 1981.

The purpose of the program is to acquire a statistical data base from which a mathematical model of the interaction between various materials and various levels of critical shot peen process parameter values on fatigue behavior can be established. The objective is for this model to predict optimum process parameter values and tolerances for specific workpieces of known material chemical and physical characteristics and operational environmental conditions.

Phase II of this program continued to address the identification of shot peen process parameters and variables whose quantitative level affects workpiece fatigue strength, and the qualification and quantification of these effects in several materials that are

extensively used in transportation vehicle structures. During the program, 1148 fatigue specimens were tested in 3 material types, 7 material groups, and 9 material sub groups (per Table 1).

Background

Historically, the published technical literature concerning shot peening has primarily focused on applied research relating to specific components or fatigue test specimens of specific materials and the benefits obtained from shot peening at specific intensity levels. The great majority of technical emphasis brought to bear on the shot peening process has been placed on the magnitude and depth of the shot peen process induced residual stress and other phenomena related to the residual stress profile. Little new information was published between 1945 and 1980 concerning the pattern of effect on workpiece fatigue strength of varying peening intensities. (See First International Conference on Shot Peening; Paris, 14-17 September, 1981, Publications.) The effect of varying levels of process variables within given intensities additionally received little attention in applicable specifications (MIL-S-13165B). In recent years, it has been generally believed that the fatigue life of shot peened specimens was relatively insensitive to changing levels of shot peening intensity. This is witnessed by the large number of technical publications relating the effects of shot peening at a given intensity with no explanation as to the choice of or detailed description of peening condition or possible further work identifying the effects of other peening conditions. (See First International Conference on Shot

Peening; Paris, 14-17 September, 1981, Publications. See also Second International Conference on Shot Peening; Chicago, 14-17 May, 1984, Preprints. See also Second International Conference on Impact Treatment Processes, 22-26 September, 1986, Publications.) In Phase I of this effort it was theorized that, while the compressive residual stresses induced by shot peening and their depth profile are certainly significant factors in developing workpiece fatigue life benefits, a highly significant and largely undefined factor, workpiece surface integrity phenomena, was involved in achieving the highest possible fatigue strength benefits from the shot peen process. The existence of this factor is resultant from certain quantitative levels of shot peening and causal to the timing and location of primary crack nucleation. It was theorized to be a critical factor in determining the shot peening process variable levels associated with optimum fatigue resistance benefits generated by the shot peening process. This metallurgical phenomenon was identified as a specific type of process induced surface deformation. It was hypothesized that, for a given set of peening conditions, if the extent of process induced surface damage were such that it affected the timing and location of primary crack nucleation, then it would also affect the amount of benefit generated by that set of shot peening conditions.

Phase I of this program investigated Aluminum Alloy 7075 in the T-6 and T-73 condition and evaluated fatigue life at varying levels of shot peening intensity. Also tested were the effects on fatigue life of saturation level as a function of Almen saturation level, and peening media size at a given Almen intensity condition. The results reported in Phase I indicated a strong statistical relationship

between a shot peen process induced surface integrity phenomenon identified as Peened Surface Extrusion Folds (PSEF) and peening intensity, and between PSEF and shot peened specimen fatigue life. ("Development of a Mathematical Model for Predicting the Percentage Fatigue Life Increase Resulting from Shot Peened Components - Phase I," Roger Simpson, April, 1985.) PSEF were first identified in technical literature in the Phase I report and were described as the lapping of the workpiece surface at the edge of the plastic deformation zone resultant from a shot particle impacting the surface. During Phase I testing, we found the size and depth of PSEF had a statistically significant negative correlation with fatigue life. ("Development of a Mathematical Model for Predicting the Percentage Fatigue Life Increase Resulting from Shot Peened Components - Phase I," Roger Simpson, April, 1985.) Due to this, significant attention during Phase II was given to the effect of varying shot peening parameter levels on surface integrity.

Phase I testing also indicated that shot peened workpiece fatigue life could be significantly more sensitive to changes in shot peen process variable levels than had previously been assumed. It also indicated that large increases in fatigue life and reduction of scatter from the unpeened state are possible when peening is closely controlled within process variable ranges which are known to produce the maximum fatigue strength benefits for the workpiece chemical and physical characteristics and load environment in question.

2.0 PROGRAM SCOPE

The testing program was executed in eight tasks aimed at investigation of the effects of major shot peening process variables on fatigue life of several materials. An outline giving the purpose and the specific materials investigated in each task is presented in the following:

2.1 Task 1

This task was executed as a precursor to the remainder of the program. It's purpose was determination of the relationship between Almen strip saturation and workpiece saturation as a function of workpiece hardness. The materials used were 7075-T6 Aluminum, AISI 4340 and 0-1 tool steels at various hardness levels.

2.2 Task 2

This task involved determination of the effect of Almen intensity on fatigue life in all of the program materials. Namely these were:

1. Commerically Pure (C.P.) Titanium
2. Titanium - 6Al-4V
3. 2024-T4 Aluminum
4. 6061-T6 Aluminum
5. 7075-T6 Aluminum
6. 7075-T73 Aluminum
7. AISI 4340 Steel, Airmelt, 20/25 HRC
8. AISI 4340 Steel, Airmelt, 34/36 HRC
9. AISI 4340 Steel, Airmelt, 40/42 HRC
10. AISI 4340 Steel, Airmelt, 48/50 HRC
11. AISI 4340 Steel, Vacuum Arc Remelt, 48/50 HRC

2.3 Task 3

This task involved investigation of the influence on initial surface condition (machined or machined and polished) on fatigue life as a function of Almen intensity. The material employed was 7075-T6 Aluminum.

2.4 Task 4

This task involved determination of the effect of varying workpiece saturation level as defined in Task 1, on fatigue life. The materials employed were:

1. Titanium - 6Al-4V
2. 2024-T4 Aluminum
3. 6061-T6 Aluminum
4. 7075-T6 Aluminum
5. 7075-T73 Aluminum
6. AISI 4340 Steel, Airmelt, 40/42 HRC
7. AISI 4340 Steel, Airmelt, 48/50 HRC
8. AISI 4340 Steel, Vacuum Arc Remelt, 48/50 HRC

2.5 Task 5

This task involved determination of the influence of impact angle of incidence on fatigue life. Materials employed were 7075-T73 Aluminum and AISI 4340 Steel, VAR, 48/50 HRC.

2.6 Task 6

This task involved determination of the effect of peening media broken particle content on workpiece fatigue life. Materials employed were 7075-T73 Aluminum and AISI 4340 Steel, VAR, 48/50 HRC.

2.7 Task 7

This task involved determining whether peening media type (glass beads versus steel shot) affected fatigue life in 7075-T73 Aluminum.

2.8 Task 8

This task involved investigating whether an increase in shot size or a secondary low intensity peening after the initial peening would affect the surface integrity of peened parts, particularly as related to PSEF size and depth.

Materials employed were 7075-T6 and 7075-T73 aluminum.

3.0 CONCLUSIONS

3.1 Task 1

This task determined the relationship between Almen saturation and workpiece saturation as a function of workpiece hardness.

A distinct positive non linear statistical relationship exists between Almen saturation and workpiece saturation as a function of workpiece hardness.

3.2 Task 2

This task determined the effect of Almen intensity on fatigue life in all of the program materials.

A distinct set of intensity conditions which clearly related to the highest fatigue life existed for specimens of all materials tested except 4340 Airmelt Steel and Commercially Pure Titanium. This set of intensity conditions is referred to in this study as Optimum Intensity Range (OIR). In 4340 Airmelt Steel, this pattern, while present, was much less clearly identified due to broad fatigue scatter within peening conditions.

The materials where an Optimum Intensity Range was clearly identified include:

1. Titanium 6Al-4V
2. 2024-T4 Aluminum
3. 6061-T6 Aluminum
4. 7075-T6 Aluminum (Polished)
5. 7075-T6 Aluminum (Lathe Turned Only)
6. 7075-T73 Aluminum
7. AISI 4340 Steel, Vacuum Arc Remelt, 48/50 HRC

There was a consistent interrelationship between failure modality, specimen fatigue life and peening intensity.

In unpeened specimens, all primary crack nucleation was at the surface of the specimen gauge section.

At intensities below OIR, primary crack nucleation was both internal and external.

At intensities within OIR, primary crack nucleation was internal.

At the first intensity condition quantitatively above OIR, some specimens had internal primary crack nucleation and some external. There was a reliable trend toward internal primary crack nucleation in specimens within these conditions to be associated with higher fatigue life than external primary crack nucleation specimens in the same peening condition.

At intensity conditions above those described in the preceding paragraph, primary crack nucleation was external.

In all specimens subjected to failure analysis, for all materials, and all intensity conditions above OIR, where OIR was present, primary crack nucleation was related to the presence of, and emanated from, a shot peening induced surface integrity degradation phenomenon referred to as Peened Surface Extrusion Folds (PSEF). ("Development of a Mathematical Model for Predicting the Percentage Fatigue Life Increase Resulting from Shot Peened Components - Phase I," Roger Simpson, April, 1985.)

In 4340 Airmelt Steel. primary crack nucleation was associated with aluminum oxide inclusions in over 90-percent of specimens subjected to failure analysis.

For commercially pure titanium, mean fatigue life of the unpeened specimens was higher than the mean fatigue life of any shot peened condition.

For commercially pure titanium, increasing peening intensity consistently produced mean fatigue life reduction.

<u>3.3 Task 3</u>

This task investigataed the influence of initial surface condition on fatigue life as a function of Almen intensity.

Lathe turned only and lathe turned and polished 7075-T6 specimens exhibited fatigue life at intensity conditions within their respective OIR's that had no apparent difference.

There was a substantial difference in the quantitative value and pattern of OIR between lathe turned only specimens and lathe turned and polished specimens.

3.4 Task 4

This task determined the effect of saturation level on fatigue life. Some materials showed a distinct pattern of variation in fatigue life as workpiece saturation was increased over 100-percent at a peening intensity within OIR. These included:

1. Titanium 6Al 4V
2. 2024-T4 Aluminum
3. 6061-T6 Aluminum
4. 7075-T6 Aluminum
5. AISI 4340 Steel, Airmelt, 40/42 HRC
6. AISI 4340 Steel, Vacuum Arc Remelt, 48/50 HRC

One material, 7075-T73, did not exhibit a distinct pattern of variation in fatigue life as workpiece saturation increased over 100-percent at a peening intensity within OIR.

3.5 Task 5

This task determined the influence of impact angle of incidence on fatigue life.

There is a dintinct difference in the fatigue life of both 7075-T73 aluminum specimens and AISI 4340 steel VAR 48/50 HRC specimens when peened at OIR at varying impact angles.

3.6 Task 6

This task determined the effect of peening media broken particle content on fatigue life.

Increases in shot broken particle content were consistently

associated with decreases in specimen fatigue life in both 7075-T73 aluminum and AISI 4340 steel VAR 48/50 HRC specimens.

3.7 Task 7

This task determined whether peening media type (glass beads versus steel shot) affected fatigue life in 7075-T73 Aluminum.

The type of shot used did not affect the fatigue life of specimens peened at OIR in a significant manner.

3.8 Task 8

This task established whether increased shot size or a secondary low intensity peening affects specimen surface integrity as it relates to PSEF size and depth at a given intensity.

While specimens peened with larger shot or a secondary low intensity peening (yielding a less coarse surface finish) have PSEF that are decreased in size for a given intensity condition, PSEF depth into the specimen remains unchanged.

4.0 GENERAL EXPERIMENTAL PROCEDURES

4.1 Materials

Material selection emphasized two criteria:

(1) Utilizing materials for which large amounts of information are available on strength characteristics, strain rates, and other physical properties.

(2) Materials which are extensively used as structural materials in transportation vehicle systems.

Since the number of material types had to be limited due to program cost and time constraints, representative materials from a broad spectrum of available materials were chosen to give as broad a technical overview as possible.

The patterns of change in optimum parameter and variable values within a given material as material chemical and physical characteristics changed was of particular importance to the anticipated predictive model that is to be finalized in Phase III of this effort.

The following material types were selected for examination (See Table 1):

1. Precipitation Hardening Aluminum
2. High Strength Steel
3. Titanium

For Task 2, all materials selected were examined. Ti 6Al-4V, 2024-T4 aluminum, and 6061-T6 aluminum were also selected for Task 4. 7075-T6 was also selected for Tasks 3, 4, and 8. 7075-T73 aluminum was also selected for Tasks 4 through 6. AISI 4340 steel, Airmelt, 40/42 HRC and 48/50 HRC were also selected for Task 4. AISI 4340 steel, Vacuum Arc Remelt, 48/50 HRC was also selected for Tasks 4 through 6.

All heat treatment represents the through-hardness condition.

Ti 6Al-4V and commercially pure titanium were chosen to compare the effects on a commonly used alloy and its base derivative.

In Task 3, 7075-T6 was chosen to compare lathe turned only and lathe turned and polished fatigue behavior when shot peened.

TABLE 1 - TEST MATERIALS

MATERIAL TYPE	MATERIAL GROUP	MATERIAL SUB-GROUPS (HEAT TREAT CONDITION)	
1. TITANIUM	1. COMMERCIALLY PURE		---
	2. 6AL-4V ALLOY		---
2. ALUMINUM ALLOY	3. 2024	3.1	T4
	4. 6061	4.1	T6
	5. 7075	5.1	T6
		5.2	T73
3. STEEL ALLOY	6. 4340 (AIRMELT)	6.1	20/25 HRC
		6.2	34/36 HRC
		6.3	40/42 HRC
		6.4	48/50 HRC
	7. 4340 (VACUUM ARC REMELT)	7.1	48/50 HRC

To establish both broad pattern recognition and a quantitative understanding of the statistical reliability of those patterns, once fatigue life versus Almen intensity patterns were established for all materials, a few of the material groups would be chosen for further tests to facilitate further pattern definition and statistical analysis.

4.2 Fatigue Test Specimens

Many variables exist in fatigue testing that can affect results. These include, but are not limited to, testing type, testing frequency, testing mode, specimen design, etc. For Phase II of this program, the combination of these factors needed to be minimized in terms of inherent testing bias in testing surface related phenomena. These criteria resulted in the selection of an axial fatigue test specimen as described in Figure 1.

4.3 Shot Peening

Shot peening was performed on three identical contractor designed, computer controlled shot peening machines using parameter tolerance controls per Table 2.

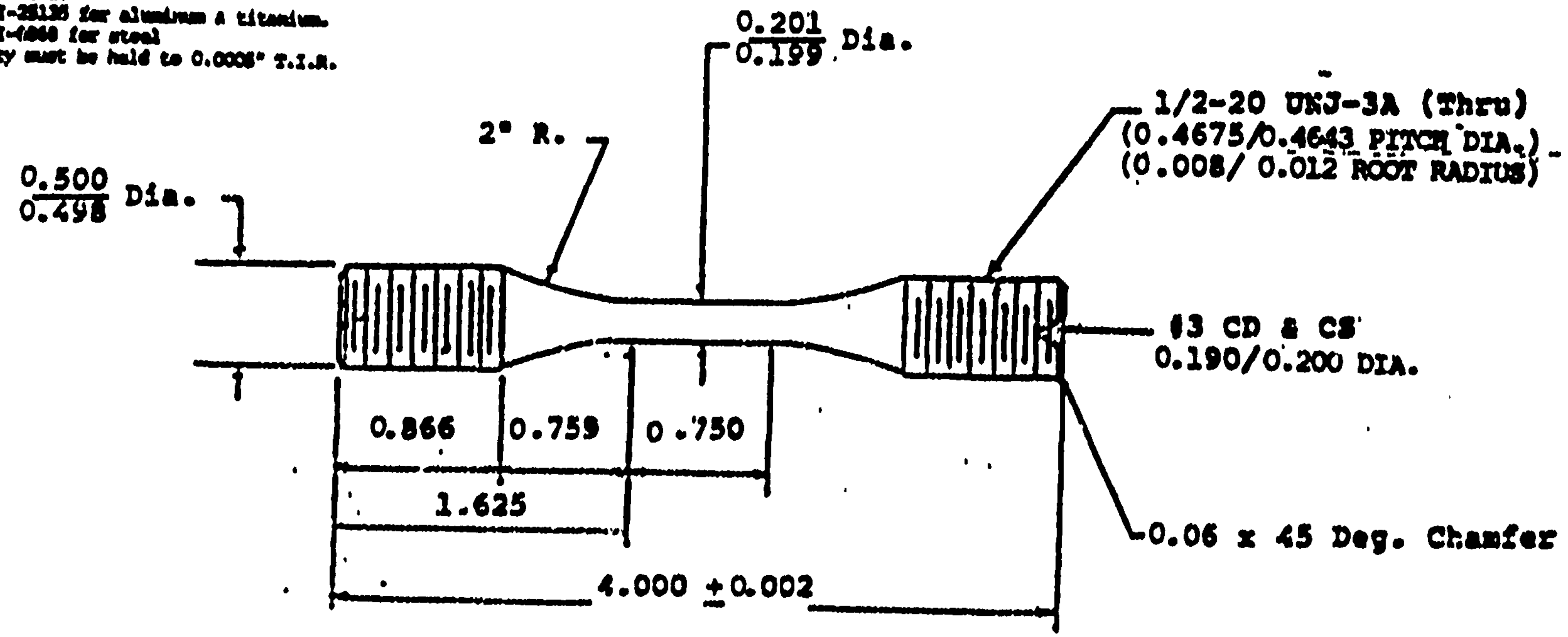
TABLE 2

SHOT PEENING PROCESS VARIABLE TOLERANCE QUALIFICATION

PROCESS VARIABLE	TOLERANCE MIL-S-13165B	TEST TOLERANCES
AIR PRESSURE	NOT STATED	+/- 1.0 PSI
TURNTABLE SPEED	NOT STATED	+/- 0.5 RPM
NOZZLE DISTANCE	NOT STATED	+/- 0.25"
ANGLE OF IMPACT	NOT STATED	+/- 2.0 DEGREES
NOZZLE ORIFICE DIA.	NOT STATED	+/- 0.002"
MEDIA FLOW		
GLASS BEAD	NOT STATED	+/- 3.0 GRAMS/MIN
STEEL SHOT	NOT STATED	+/- 3.0 OZ/MIN
STROKER SPEED	NOT STATED	+/- .25"/MIN
CYCLE TIME	NOT STATED	+/- 1.0 SECOND
ALMEN STRIP		
FLATNESS	+/- 0.0015"	+/- 0.0001"
THICKNESS	+/- 0.001"	+/- 0.001"
HARDNESS	+/- 3 HRC	+/- 1.5 HRC
ALMEN GAUGE		
MOUNTING PLANE	+/- 0.002"	+/- 0.0001"

Tests were run prior to peening any specimens to establish cumulative process tolerance limits. Quantification of the relationship of critical process parameters to Almen intensity and saturation resulted in establishing the process tolerances in Table 2. When maintained within their respective tolerance ranges, variance did not affect Almen intensity more than +/- 0.0004" or saturation more than +/- 10%.

1. After receipt of raw stock, test & certify for mechanical & chemical properties per applicable military and/or industrial specifications. (Ex: 2024-T4 Aluminum per MIL-S-QQA-225/6)
2. Heat treat aluminum per Aluminum Standards & Data, 1984, 8th Edition.
3. Heat treat steel per MIL-H-6875
4. Grind gage length and adjoining radii on steel specimens to a 16-20 RMS finish per Low Stress Grinding Procedures, Metcut Research & Assoc., Cincinatti, Ohio.
5. Polish gage length and adjoining radii on aluminum and titanium specimens circumferentially to a 16-20 RMS finish per the following procedure: #320 grit paper @ 1000 RPM to remove tool marks followed by #400 grit paper @ 1000 RPM followed by #600 grit paper @ 1000 RPM.
6. After grind and/or polish but before peening or testing, non-destructively inspect specimens:
   a. Per MIL-I-25135 for aluminum & titanium.
   b. Per MIL-I-6868 for steel
7. Concentricity must be held to 0.0005" T.I.R.



TEST SPECIMEN SURFACE CONDITION AND FINISH

Lathe turned only	- LT	- 60-65 RMS
Lathe turned and circumferentially polished	- LT & P (C)	- 16-20 RMS
Lathe turned and O.D. ground	- G	- 3035 RMS
Lathe turned, O.D. ground and longitudinally polished	- G & P (L)	- 10-15 RMS
Lathe turned, O.D. ground and circumferentially polished	- G & P (C)	- 16-20 RMS

FIGURE 1 - AXIAL FATIGUE SPECIMEN DRAWING

Individual test specimens were selected for a given peening intensity using a random numbers table to remove selection bias. Specimens were subsequently placed in an envelope which was tied closed and identified on its face with the specimen identification numbers, peening condition desired, specimen material type, the percent of Almen saturation necessary to achieve 100-percent workpiece saturation per the equation derived in Task 1 and any other pertinent processing information. Accompanying paperwork consisted of a shot peen process procedure sheet, Almen test strip record sheet, fatigue test specimen in-process record sheet and a fatigue test specimen peening log. Shot peen machines were calibrated per MIL-STD-45662. Shot peen machine setup was inspected daily per MIL-I-45208A prior to processing specimens. The contractor's USAF approved MIL-Q-9858 Quality Assurance System was utilized. In all respects MIL-S-13165B, MIL-G-9954A and MIL-STD-852 requirements were met or exceeded.

Cast steel shot was pre conditioned before use and conformed to MIL-S-13165B Table 1 for sizing throughout specimen processing. Glass bead conformed to MIL-G-9954A. Almen test fixtures were machined per standard MIL-S-13165B Almen block dimensions and heat treated to 60 HRC minimum hardness. Specimen holding fixtures were machined from Ultra High Molecular Weight polymer. Specimens were peened per the contractors Quality Assurance System, in 10-percent or less increments of the cycle time necessary to achieve Almen saturation. ("A New Concept for Defining Optimum Levels of a Critical Shot Peening Process Variable," Roger Simpson, Gordon Chiasson; Second International Conference on Impact Treatment Processes, 22-26 September, 1986, p.101.) Visual inspection for 100-percent workpiece coverage was conducted using a 70X Bausch & Lomb Stereo 7 binocular microscope

after each 10-percent or less increment. Full specimen coverage was verified by at least two personnel qualified per the contractor's Quality Assurance System. After peening was completed the specimen was immediately placed into an air tight specimen tube holding an individual specimen. Steel specimens were coated with a rust-inhibiting light machine oil before being placed in tubes.

4.4 Fatigue Testing

Fatigue testing was accomplished at the contractor's facility and the University of Wisconsin utilizing Sonntag type mechanical fatigue test machines. The lower flex plate in the 5X multiplier in tests conducted at the University of Wisconsin was strain gauged and calibrated to monitor loading during each test using an oscilloscope. A Straincert Precision Load Cell Model FFL (15,000# capacity) or a Lebow Precision Load Cell Model 3161 (10,000# capacity) in conjunction with a Datronic Signal Conditioner Model 3370 was incorporated into the pull train of fatigue testing at the contractor's facility.

Fatigue testing was performed in axial tension/tension mode at 30 Hz frequency with a load ratio, R = 0.1.

In all specimens except titanium, pull trains were spring loaded to retract the failed specimen halves and prevent fracture surface damage.

The maximum stress level utilized for specific material conditions was established by testing at least six unpeened specimens. Targeted unpeened control specimen fatigue life was 100,000 cycles, with stress levels adjusted to obtain unpeened control specimen fatigue life near this target. All fatigue testing procedures conformed to ASTM specifications E-466 and E-467.

4.5 Post-Fatigue Specimen Examination and Test Specimen Fatigue Failure Analyses

Fractography was performed at the contractor's facility utilizing a 70X Bausch & Lomb Stereo 7 Binocular microscope and a Quickscan 1000 scanning electron microscope; and at the University of Michigan utilizing a Hitachi scanning electron microscope. Metallography was performed at the contractor's facility utilizing a Bausch & Lomb metallograph and at a local materials laboratory utilizing a Hitachi metallograph.

4.6 PSEF Identification, Procedures

In describing procedures for identifying the surface integrity phenomena referred to as Peened Surface Extrusion Folds (PSEF), a description of the formative mechanics of PSEF is helpful.

As each peening shot strikes the workpiece, it displaces workpiece material plastically in a radial pattern, centering on the impact, assuming 90-degree impact angle.

At relatively low shot peening intensity levels, even highly malleable workpiece materials. such as aluminum or titanium, will be deformed such that the peaks and valleys created by overlapping shot impingements form a continuous surface largely uninterrupted by laps or folds in the surface. Note the presence of machining marks in Figure 2 and the very small surface folds in Figure 3.

In harder materials, the total amount of plastic deformation is lower, much like a Brinnell Hardness Test, for a given intensity with the size of individual shot impact craters and associated radial displacement of workpiece material being reduced. In very hard materials, the plastic deformation caused by shot impacts can become very difficult to see even at high magnification. Note the presence

FIGURE 2 - 7075-T73 AT 0.0020A AT 200X (SURFACE)

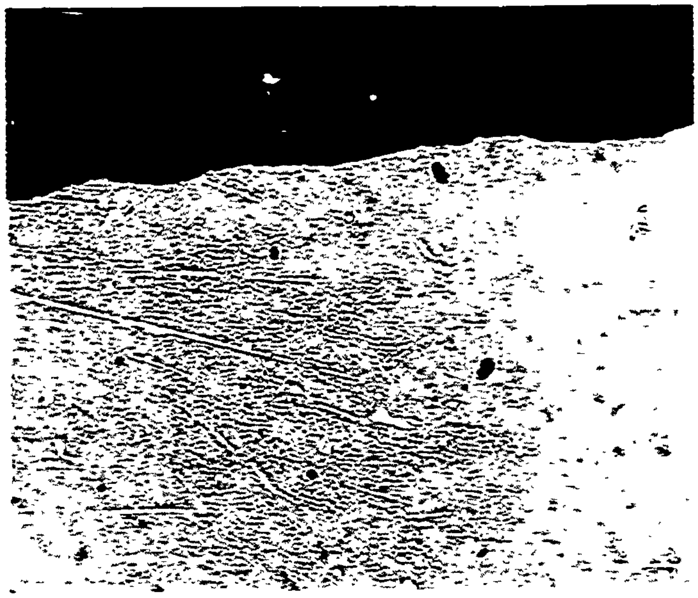


FIGURE 3 - 7075-T73 AT 0.0020A AT 700X (CROSS SECTION)

FIGURE 4 - 4340 STEEL VAR 48/50 HRC AT 0.0020A AT 200X (SURFACE)

FIGURE 5 - 4340 STEEL VAR 48/50 HRC AT 0.0020A AT 700X (CROSS SECTION)

of large machining marks in Figure 4 and the very small surface fold in Figure 5.

Figures 6, 7, 8, and 9 illustrate the increasing level of plastic deformation and radial displacement that occurs from the sum of many individual shot impact craters as peening intensity increases from zero. Note the presence of machining marks in the unpeened and 0.0020A conditions, and that these machining marks have been obliterated in the 0.0040A and 0.0060A conditions.

At some point, all else equal, as the total energy transferred by individual shot impacts increases (i.e., peening intensity increases) and the resultant plastic deformation of the workpiece surface and associated radial displacement of material increases, the material associated with the edges of a shot impact crater begins to be extruded over surrounding material at the edge of the impact crater rim in conceptually much the same way as an ocean wave crests and breaks (Figure 10). Note the significant amount of grain flow in, near, and under the "wave" or PSEF.

These laps were first identified in technical literature in "Development of a Mathematical Model for Predicting the Percentage Fatigue Life Increase Resulting from Shot Peened Components - Phase I," (the initial phase of this program) and identified as PSEF to differentiate them from machine marks and other types of surface folds and laps.

Since Phase I, other literature has focused on the identification of qualitative changes occurring in workpiece surface integrity as shot peening intensity changes. Of particular interest are the excellent photomicrographs in "Selected Examples on the Topography of Shot Peened Metal Surfaces," W. Kohler, Dornier System GmbH, Third

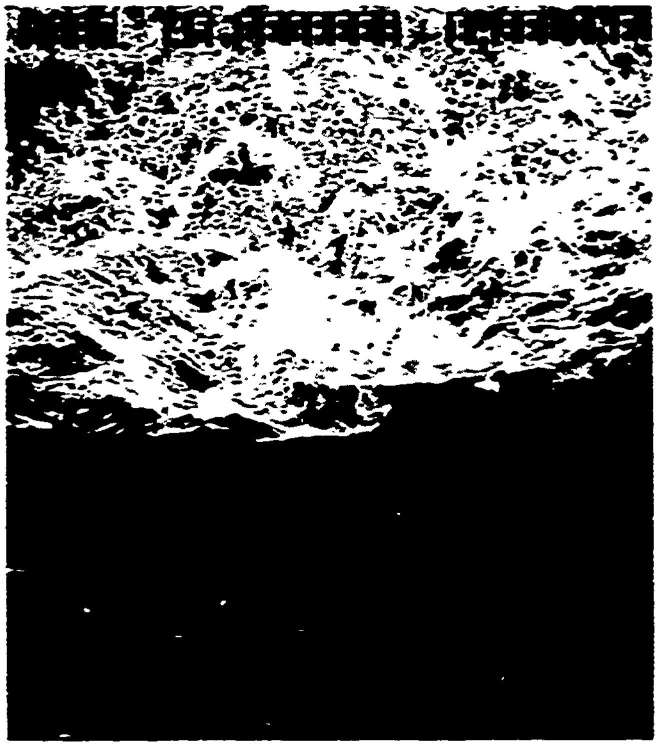


FIGURE 6 - 7075-T6 ALUM., UNPEENED AT 50X, TOOL MARKS PRESENT

FIGURE 7 -7075-T6 ALUM. AT 0.0020A AT 50X, TOOL MARKS PRESENT

FIGURE 8 -7075-T6 ALUM. AT 0.0040A, AT 50X, TOOL MARKS & PSEF NOT PRESENT

FIGURE 9 -7075-T6 ALUM. AT 0.0060A AT 50X, PSEF PRESENT

International Conference on Shot Peening, 1987.

FIGURE 10- 7075-T6 AT 0.0105A (PHASE I), NOTE GRAIN FLOW

In order to facilitate discussion of PSEF identification, several definitions are given below:

PEENED SURFACE EXTRUSION FOLDS (PSEF):

A lap or fold in a metal surface at the edge of a peening shot impact dent or crater caused by the absorption and conversion of energy from a peening shot impact into plastic deformation.

PSEF SIZE:

The distance from the deepest point of a surface lap or fold meeting the requirements of PSEF definition above, to the highest peak or edge directly adjacent to, and forming a side of, the lap or fold (Figure 11).

PSEF DEPTH:

The physical distance from the deepest point of a surface lap or fold meeting the requirements of PSEF definition above, to the approximate pre processing surface (Figure 11).

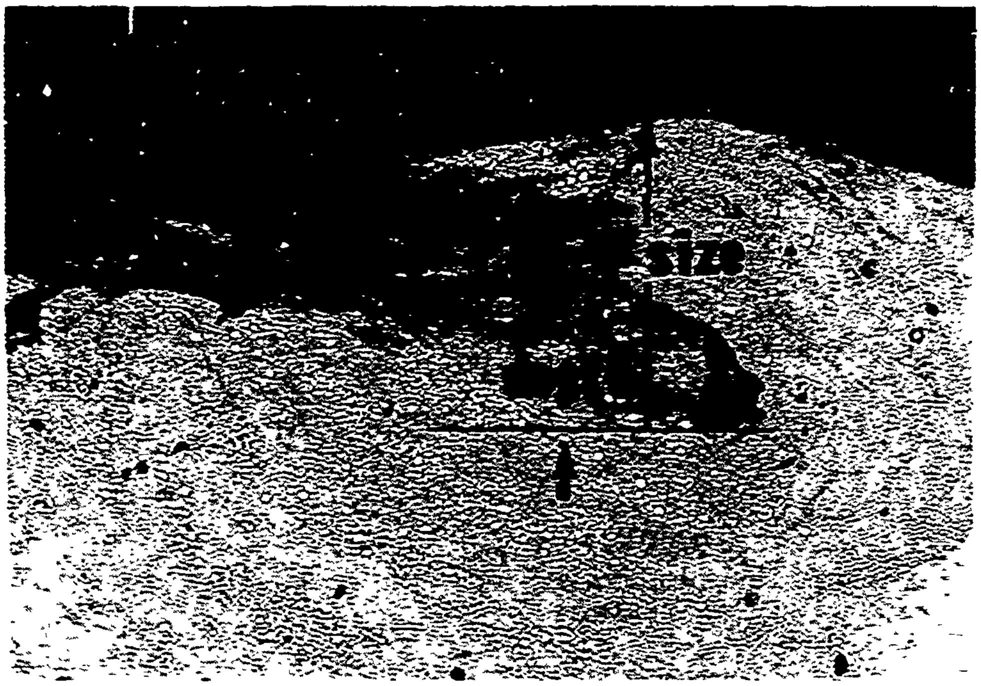


FIGURE 11 DESCRIPTION OF PSEF SIZE AND DEPTH

The goals of Phase II of the research program did not include quantification of size and depth of PSEF; but rather to make qualitative judgements as to the size and depth of PSEF associated with varying peening conditions.

Important concepts in examining PSEF's are:

(1) Shot impacts are not placed in an organized fashion in microscopic areas of the workpiece surface.

(2) One hundred percent workpiece saturation requires 100-percent cold working of the surface.

(3) Due to (1) and (2) above, shot impacts overlap each other. As such, PSEF can be seen in metallographic sectioning within the radius of another shot impingement (Figure 12).

(4) PSEF can be hidden from surface examination (Figure 13). There are, in fact, certain peening conditions which, while yielding surfaces in which PSEF are not visible from surface examination, have extensive surface laps and folds meeting the requirements of PSEF definition (See Task 8 discussion).

(5) PSEF need not have significant depth to form enough of a stress concentration to nucleate cracks, depending on the fracture toughness of the material in question. See Figure 14 and note the crack emanating from the PSEF on the surface of the workpiece in the right side of the photomicrograph.

Equally important as defining what PSEF are, is defining what PSEF are not. PSEF are distinctly different from either the angular impingements caused by fractured, angular, or deformed shot particles, or surface strain cracking due to prolonged cold work. Figures 15, 16, 17, and 18 are examples of PSEF photomicrographs in peened surfaces. These PSEF are visible from surface examination.

During testing, PSEF identification for given peening conditions and material types was accomplished after fatigue testing by scanning electron microscopy examination of the peened surface and transverse metallographic sectioning of the specimen gauge section. Photomicrographs of PSEFs found were kept as a permanent record.

FIGURE 12 - 7075-T73 AT 0.0140A, PSEF IN BOTTOM OF ANOTHER IMPINGEMENT

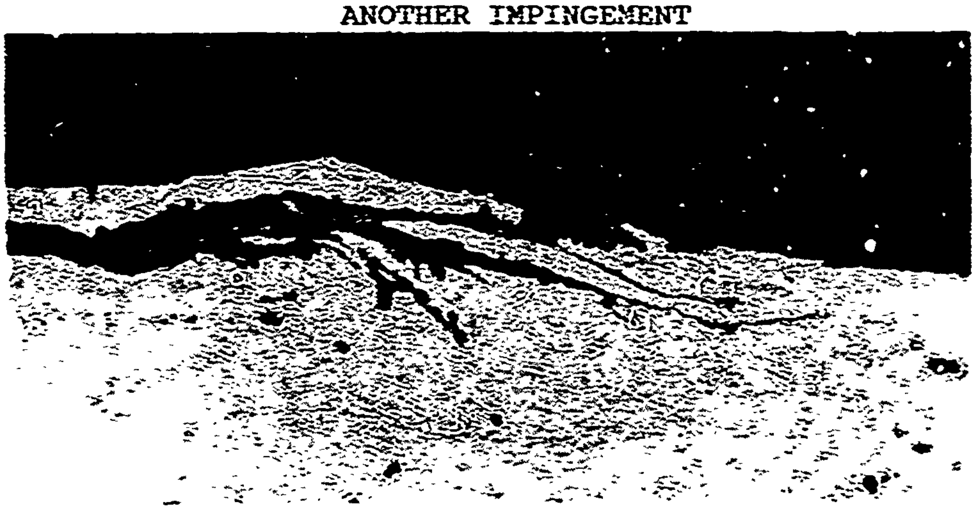


FIGURE 13 - 7075-T6 AT 0.0180A, LAP COVERS SEVERE SURFACE ANOMALIES

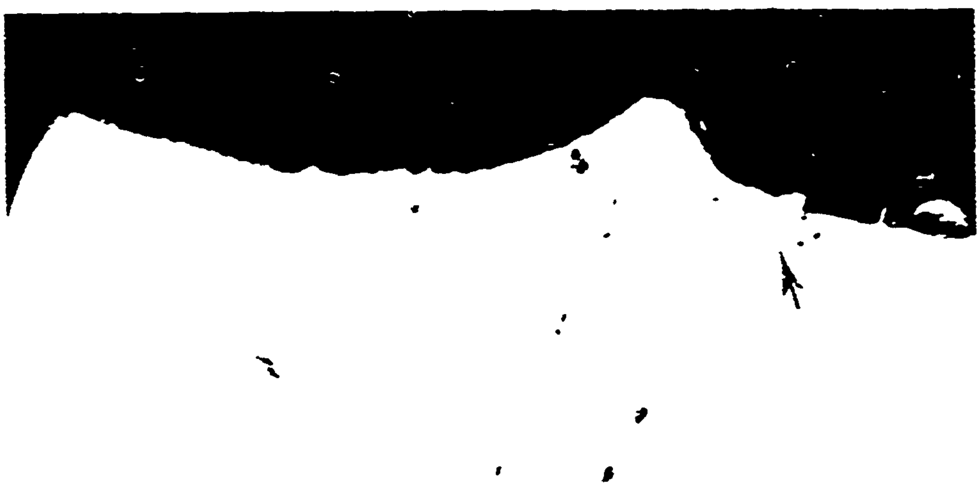


FIGURE 14 - 7075-T73 AT 0.0060A, ARROW DENOTES CRACK EMANATING FROM PSEF

FIGURE 15 - Ti 6AL-4V AT 0.0120A
PSEF PRESENT, 200X

FIGURE 16 - Ti 6AL-4V AT 0.0120A
FIGURE 15 AT 1300X

FIGURE 17 - 4340 STEEL VAR 48/50
HRC AT 0.0120A - SEVERE PSEF, 400X

FIGURE 18 - 4340 STEEL VAR 48/50
HRC AT 0.0120A - SEVERE PSEF, 400X

4.7 Failure Analysis

Each specimen, except those fatigue tested at the University of Wisconsin, was examined for failure mode by 50X binocular microscope and at least two trained technicians. Where any non concurrence or lack of certainty concerning the failure mode existed, specimens were subjected to scanning electron microscopy examination. Of particular importance to the Phase II effort was the establishment of trends associated with primary crack nucleation site characteristics. During failure analysis of Phase II specimens, the physical structures associated with primary crack nucleation fell into three categories:

(1) Internal -- This failure mode is illustrated by the typical photomicrographs of internal failure shown in Figure 19. These are representative of the type of intergranular failure found in specimens which had internal primary crack nucleation not associated with foreign inclusions.

(2) External -- This category is formed by two sub categories. They are:

  (a) Machine polish or grind marks left over from specimen manufacturing. (Figures 20 and 21.)

  (b) PSEF at primary crack nucleation site. Figures 22, 23, 24, and 25 are increasing magnification photomicrographs of the primary crack nucleation site on a 7075-T73 aluminum specimen. Note the ragged appearance of the PSEF edge in Figure 25.

(3) Inclusion -- This category of failure mode was found strictly in AISI 4340 (Airmelt) where aluminum oxide inclusions were associated with primary crack nucleation with one exception, that being a submerged carbide inclusion in one specimen of AISI 4340 (VAR). Figures 26A and 26B are increasing

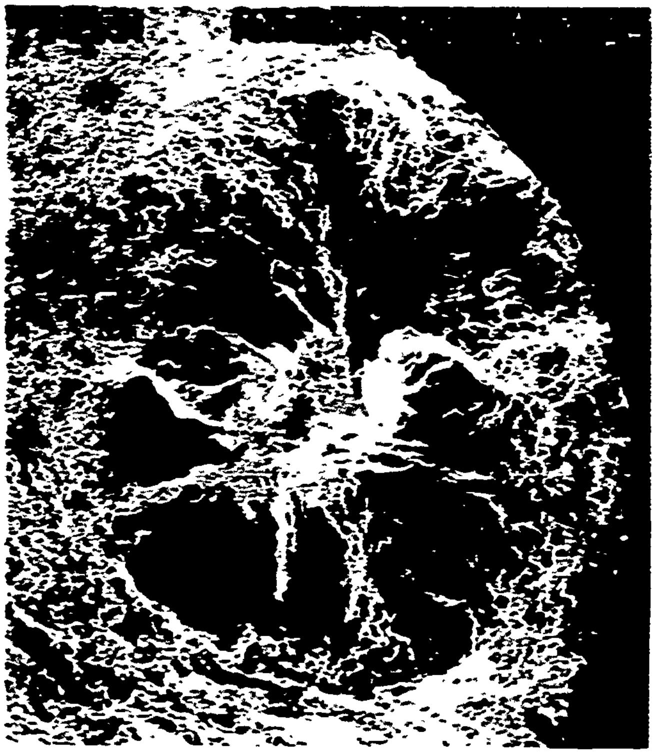


FIGURE 19 - 7075-T73 AT 0.0020A AT 20X, INTERNAL FAILURE MODE, TYPICAL INTERGRANULAR CONICAL FAILURE

FIGURE 20 - 7075-T6 UNPEENED, EXTERNAL FAILURE MODE AT MACHINE MARK, 200X

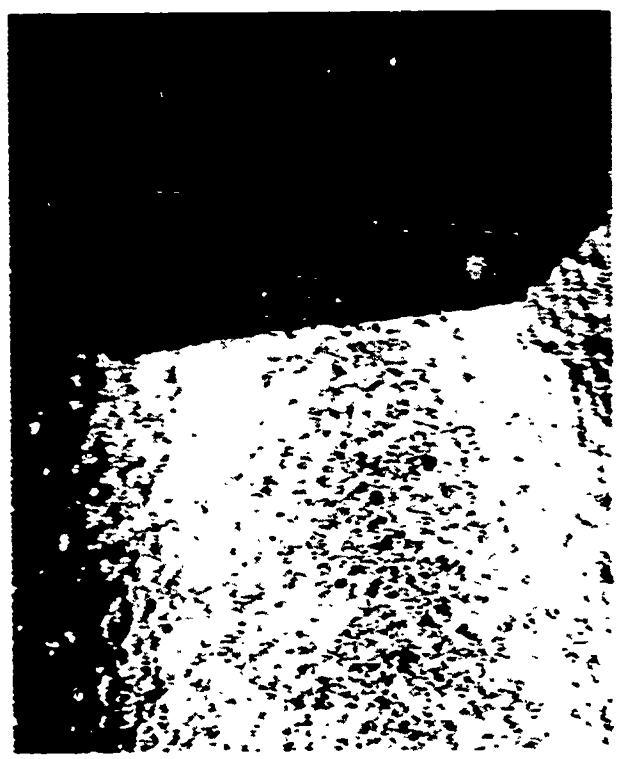


FIGURE 21 - 4340 STEEL AIRMELT 40/42 HRC AT 0.0060A, EXTERNAL FAILURE MODE AT MACHINE MARK - PEENING DID NOT OVERCOME RISER DUE TO GRIND MARK, 40X

FIGURE 22- 7075-T73 ALUM AT 0.0140A
150X, EXTERNAL INITIATION AT PSEF

FIGURE 23- 7075-T73 ALUM AT 0.0140A
FIGURE 22 AT 350X - PSEF

FIGURE 24- 7075-T73 ALUM AT 0.0140A
FIGURE 22 AT 1000X - PSEF

FIGURE 25- 7075-T73 ALUM AT 0.0140A
FIGURE 22 AT 1970X - PSEF

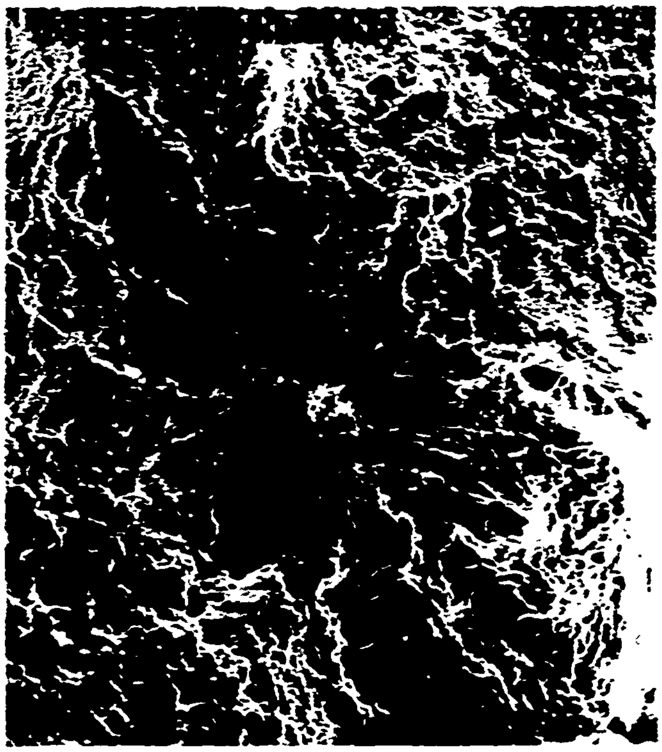


FIGURE 26A - 4340 AIRMELT STEEL 48/50 HRC AT 0.0080A, 100X, INTERNAL INITIATION AT ALUMINUM OXIDE INCLUSION

FIGURE 26B- 4340 AIRMELT STEEL 48/50 HRC, 0.0080A, INCLUSION, FIGURE 26 AT 1000X

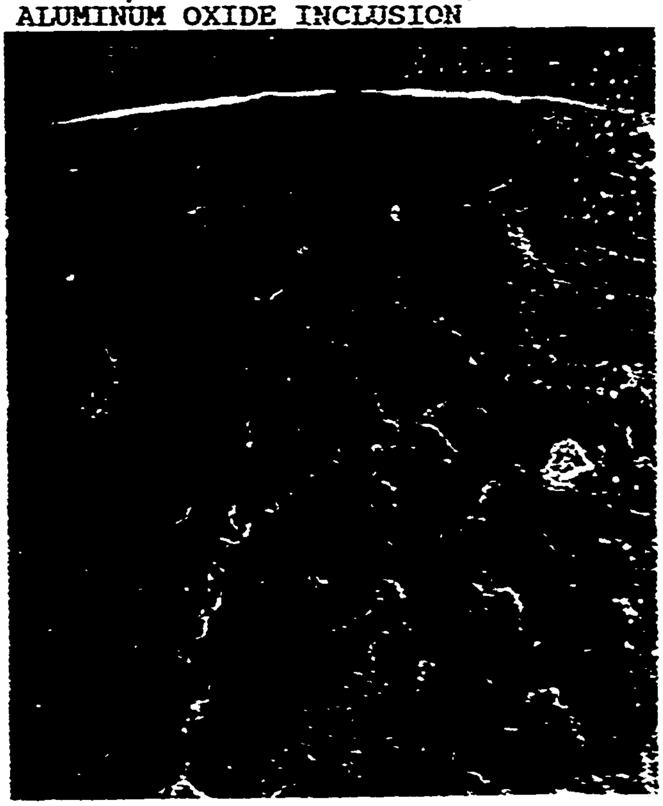


FIGURE 27- 4340 VAR STEEL 48/50 HRC, 0.0080A, SURFACE INITIATION AT CARBIDE INCLUSION, 100X

magnification photomicrographs of an internal aluminum oxide inclusion and the associated fracture lines around it. Figure 27 shows a submerged sub surface carbide inclusion with associated fracture lines.

Failure analysis was accomplished on various randomly selected specimens throughout scatter ranges and overtly selected specimens at the top and bottom of scatter ranges until reliable trends were established.

5.0 SPECIFIC STUDY GROUP PROCEDURES, RESULTS, DISCUSSION

5.1 TASK 1: DETERMINATINON OF WORKPIECE SATURATION AS A FUNCTION OF ALMEN SATURATION

Intuitively, we can recognize that if a workpiece material is relatively harder than the standard Almen Strip, workpiece saturation will occur later in the blast cycle, all else equal, due to the relatively smaller shot impingement diameters in the workpiece. Conversely if the workpiece hardness is less than that of the Almen Strip, workpiece saturation will occur sooner because of the relatively larger shot impingement diameters in the workpiece.

Tests were performed on 7075-T6 Aluminum, AISI 4340 Steel and Type 0-1 tool steel to quantify these effects.

A 3-inch diameter specimen and a peening machine with a large cabinet interior were chosen to mitigate against secondary impacts markedly increasing the difference between workpiece coverage and workpiece saturation. Almen strips were mounted in a 3-inch diameter Almen strip fixture (simulating the specimen geometry), 3 inches long, such that the outward face of the strip was at the 3-inch-diameter and longitudinally parallel to the axis of the cylinder. Nozzle to workpiece distance was 10 inches which produced a 7/8 inch diameter blast pattern. Speed of rotation of the workpiece was 30 RPM on the workpiece cylinder's axis. Nozzle vertical oscillation speed was 12 inches/minute, 6 inches of total travel. (This rotation speed/oscillation speed relationship was established so as to eliminate primary and secondary patterns on the workpiece, and was

calculated to cause less than 1 degree change in impact angle when accounting for nozzle motion and part rotation). The Almen saturation curve was established.

The intensity of peening was 0.0088N +/- 0.00050N. Peening media used was S-70 cast steel shot per MIL-S-13165B Table I.

After the Almen saturation curve was established each specimen was peened in 10-percent increments of the time necessary to achieve 100-percent Almen saturation on a test strip. After each 10-percent increment, two individuals independently examined each cylinder to determine when 100-percent workpiece coverage first occurred. Twenty-four specimens were peened, four of each material/hardness and the time to reach 100-percent on each one was recorded. All Rockwell "C" hardnesses (HRC) were converted to the Brinell scale (HBN) to facilitate statistical analysis.

The results shown in Figure 28 clearly indicate that a strong positive relationship exists between the relative time to achieve 100-percent workpiece saturation (expressed as a percentage of Almen strip saturation time) and workpiece hardness.

Analysis of the data shows a 0.97 explained variance and a correlation coefficient of 0.98+. Both numbers hold statistical significance. Actual cycle time for peening specimens of varying hardnesses was consistent with the data generated.

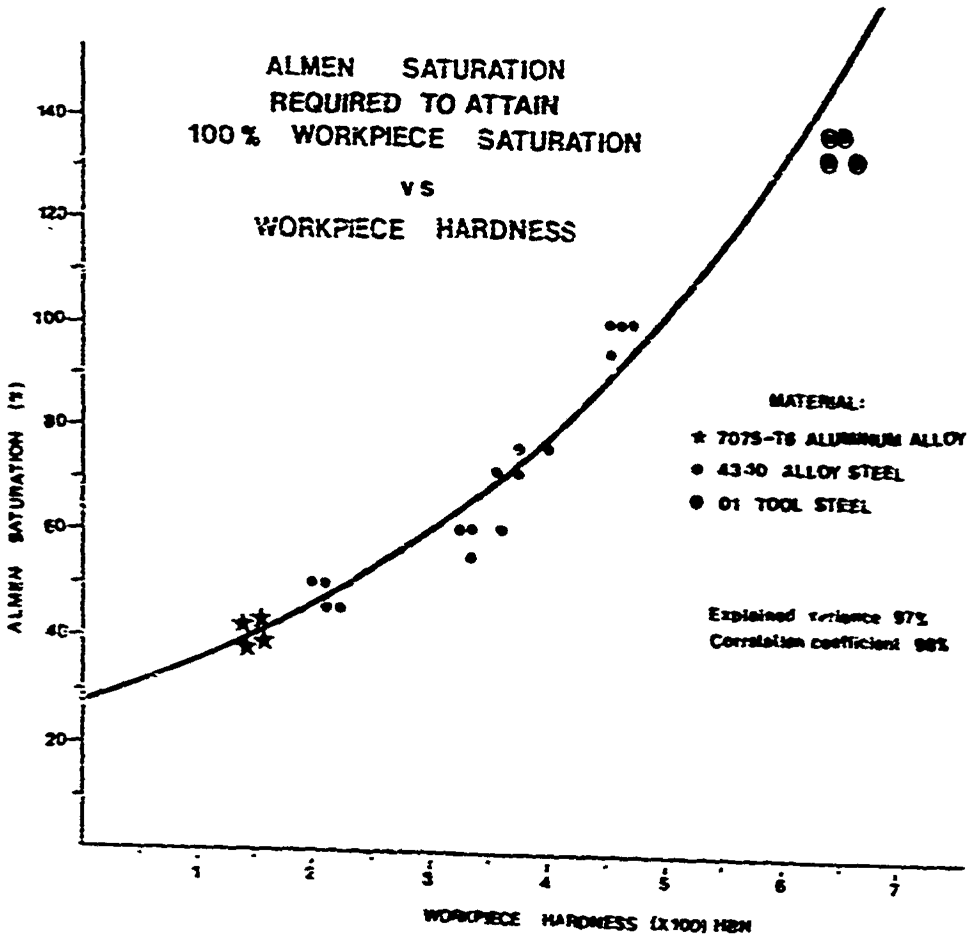


FIGURE 28: ALMEN SATURATION REQUIRED TO ATTAIN 100% WORKPIECE SATURATION VS. WORKPIECE HARDNESS

5.2 TASK 2: FATIGUE LIFE VERSUS ALMEN INTENSITY

The purpose of Task 2 was to identify the statistical relationship between changes in Almen peening intensity and fatigue life for each test material.

During Phase I testing, it was determined that, for the workpiece chemical characteristics and load type used in testing, as Almen intensity was increased from 0 (zero) to 0.0120A, a distinct set of Almen intensity conditions yielded higher mean fatigue life than all other Almen intensities or ranges of Almen intensity. Phase II, Task 2 expanded this.

5.2.1 Commercially Pure Titanium

Test data were obtained at a maximum stress condition of 85.3 ksi. Figure 29 and Table A-1 (Appendix A) present the fatigue life versus Almen intensity data.

RESULTS

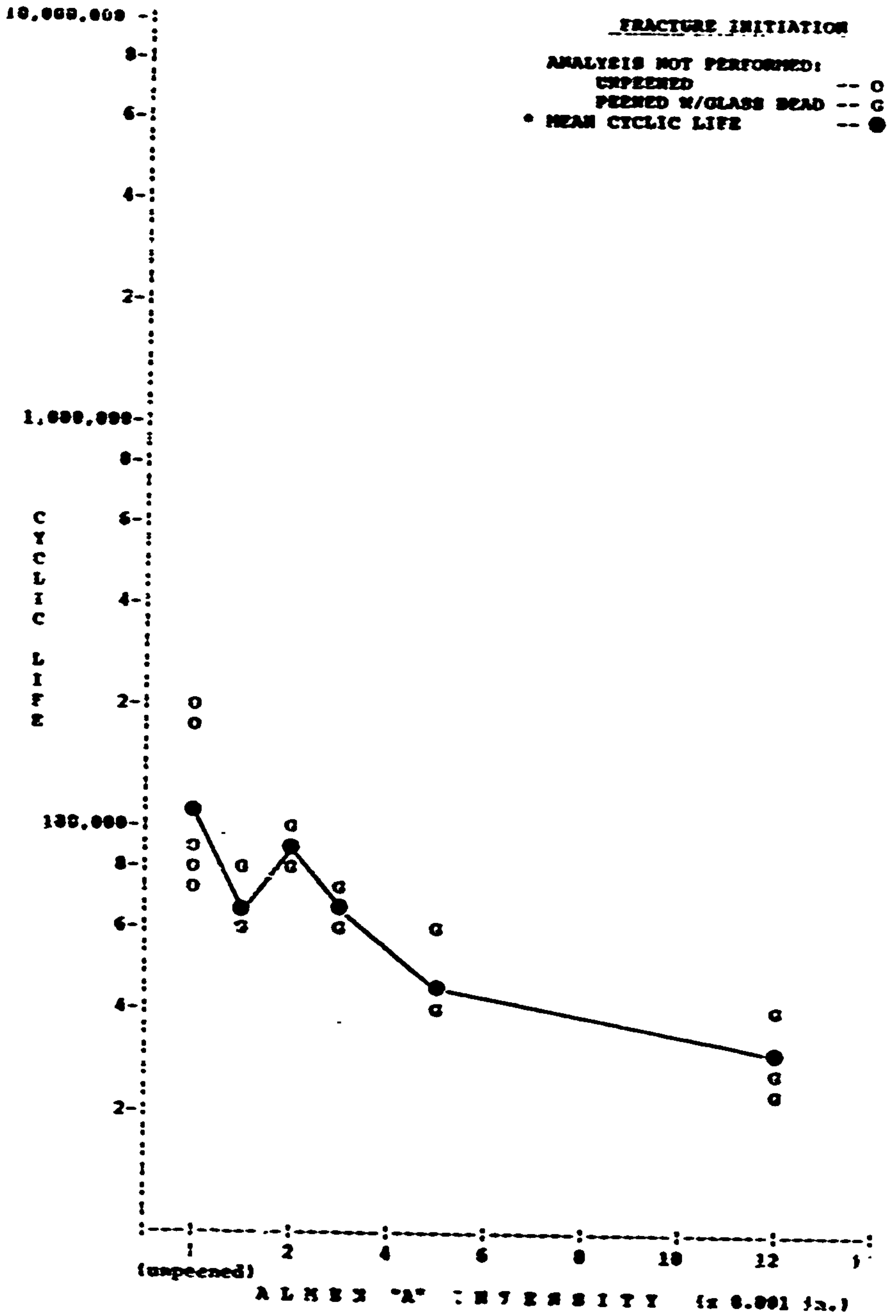
Unpeened control specimens exhibited a mean fatigue life of 129,000 cycles. As peening intensity increased, fatigue life decreased, with all intensity conditions having lower mean fatigue life than unpeened control specimens.

5.2.2 Ti 6AL-4V Alloy

Fatigue testing was conducted at the University of Wisconsin. The test data were obtained at a maximum stress condition of 140 ksi. Figure 30 and Table A-2 (Appendix A) present the fatigue life versus Almen intensity data.

RESULTS

Unpeened control specimens exhibited a mean fatigue life of 922,000 cycles. (This value is artificially high due to the one specimen which had a fatigue life of 5,711,000 cycles.) As peening

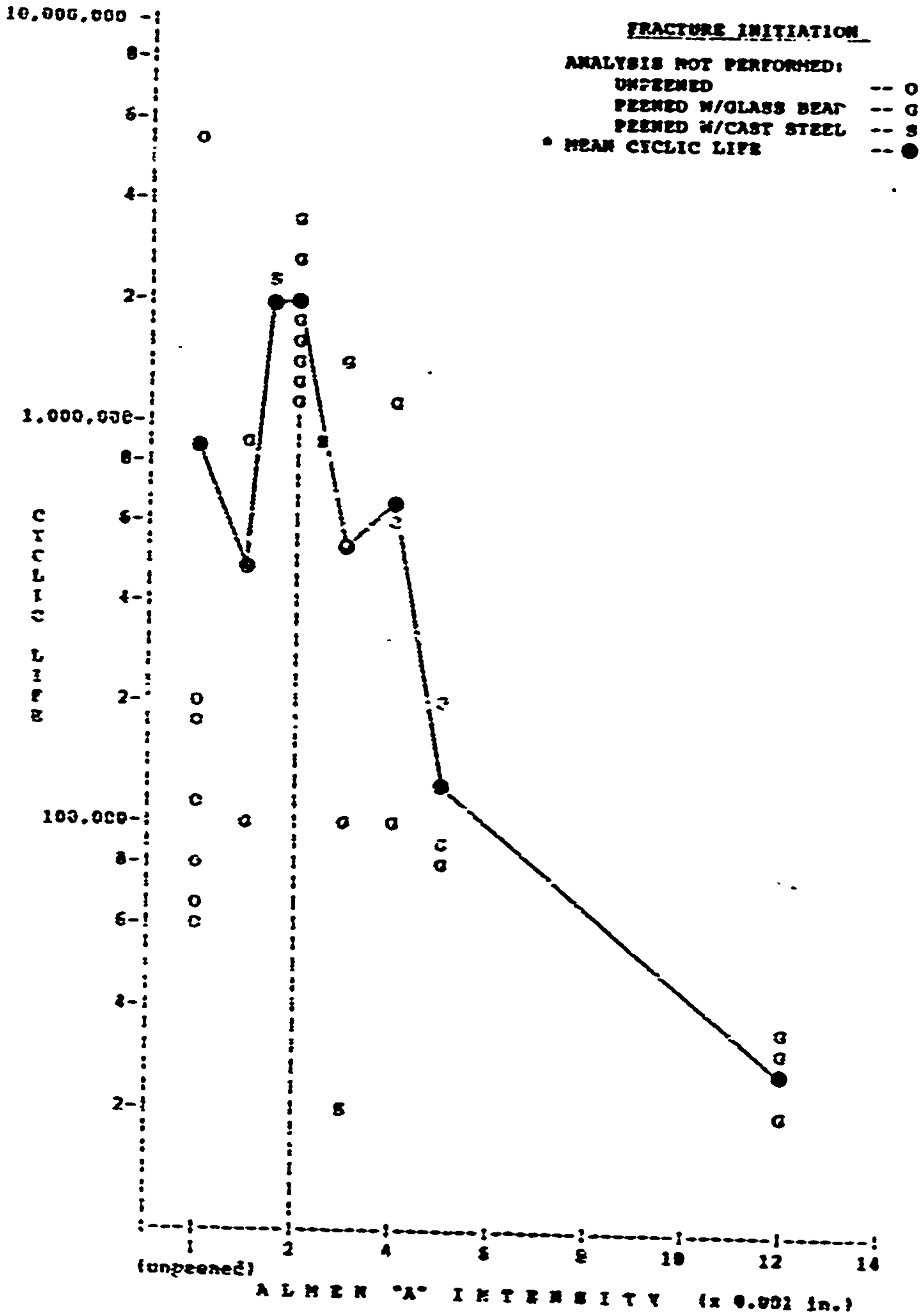


*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

TEST GROUP :	FATIGUE LIFE VERSUS INTENSITY (TASK 2)
MATERIAL :	TITANIUM (C.P.) 34/36 HRC, (LOT C-0016)
SPECIMEN SURFACE :	LATHE TURNED & POLISHED (C)
WORKPIECE SATURATION :	100%
ANGLE OF IMPACT :	90 DEGREES
MAXIMUM STRESS (KSI) :	85.3

FIGURE 29

FATIGUE RESULTS VS. INTENSITY, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR TITANIUM (C.P.)



*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

TEST GROUP	:	FATIGUE LIFE VERSUS INTENSITY (TASK 2)
MATERIAL	:	6AL - 4V TITANIUM 41/42 HRC (LOT C-0015)
SPECIMEN SURFACE	:	LATHE TURNED & POLISHED (C)
WORKPIECE SATURATION	:	100%
ANGLE OF IMPACT	:	90 DEGREES
MAXIMUM STRESS (KSI)	:	140

FIGURE 30

FATIGUE RESULTS VS. INTENSITY, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 6AL - 4V TITANIUM

intensity increased up to about 0.0020A, fatigue life increased. As peening intensity increased above 0.0020A, fatigue life decreased. Specimens peened at an intensity of 0.0120A, the high end of intensity range specified in MIL-S-13165B, exhibited fatigue life below that of unpeened specimens and specimens peened at lower intensities. While the low value specimen in the 0.0030A peening condition is believed to be an aberration, the testing done at University of Wisconsin did not keep fracture faces from contacting each other after failure, and as such failure analysis was not possible.

Based on post peening specimen examination, at the 0.0020A intensity condition, PSEF were very small relative to higher intensity conditions, or were not visibly present (Figure 31).

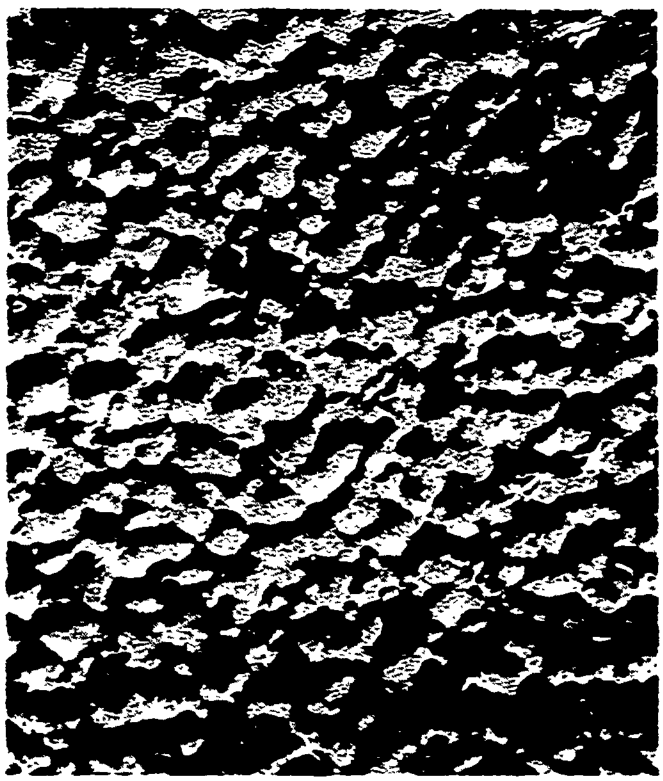


FIGURE 31 Ti 6AL-4V AT 0.0020A AT 200X, INSIGNIFICANT PSEF FORMATION

5.2.3 Aluminum Alloy 2024-T4

Test data were obtained at a maximum stress condition of 47 ksi. Figure 32 and Table A-3 (Appendix A) present fatigue life versus Almen intensity data.

RESULTS

Unpeened control specimens exhibited a mean fatigue life of 157,000 cycles. The peening intensity condition of 0.0010A had the highest fatigue life. Peening conditions above 0.0020A had mean fatigue life lower than unpeened control specimens.

Specimen failure analysis indicated specimens with fatigue life above 1,000,000 cycles had internal fracture initiation sites. Unpeened control specimens and specimens treated with intensity conditions above 0.0030A indicated surface initiation sites.

5.2.4 Aluminum Alloy 6061-T6

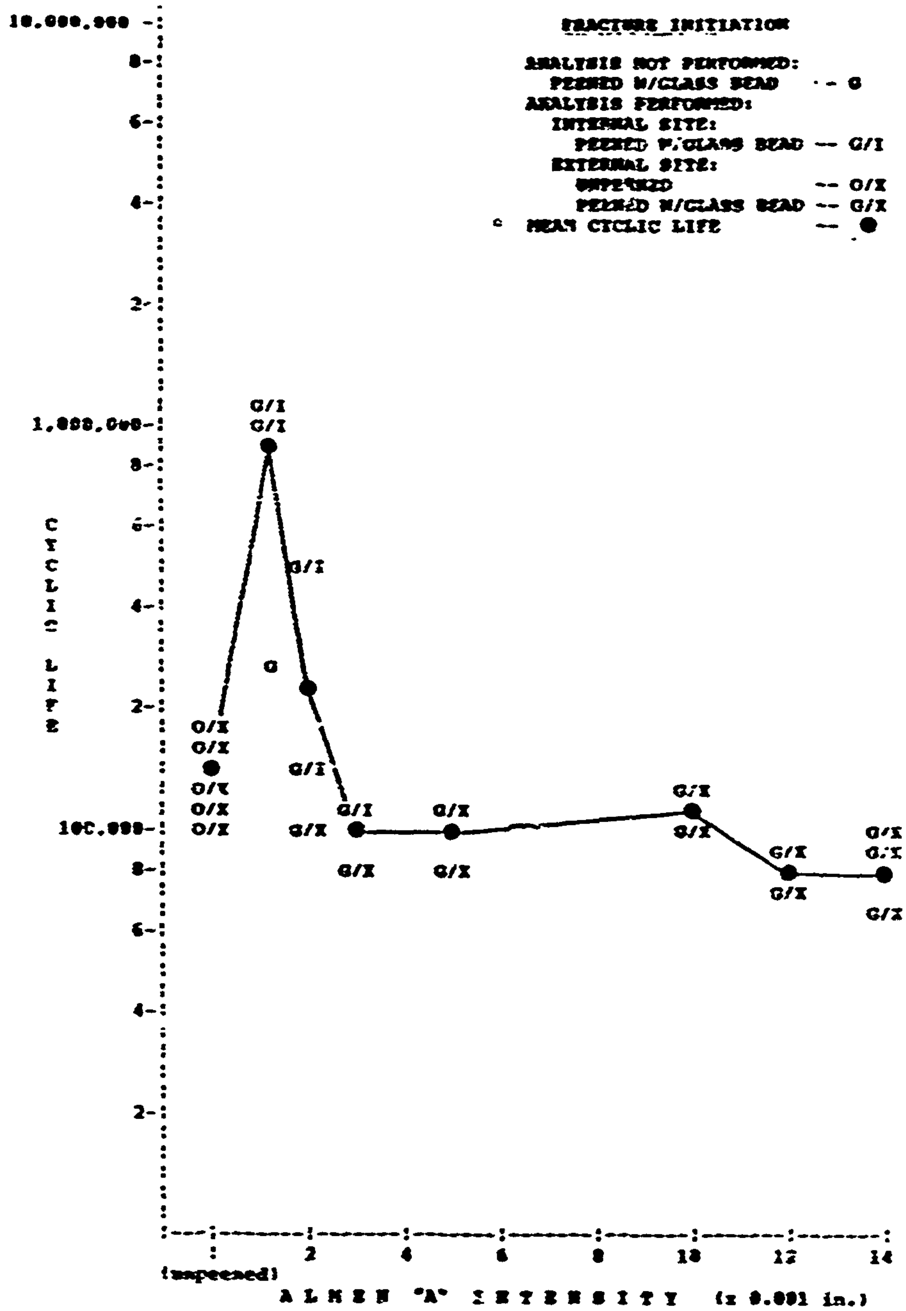
Test data were obtained at a maximum stress condition of 40 ksi. Figure 33 and Table A-4 (Appendix A) present fatigue life versus Almen intensity data.

RESULTS

Unpeened control specimens exhibited a mean fatigue life of 239,000 cycles. All peened conditions exhibited narrow scatter band ranges. Fatigue life for all specimens in the 0.0020A intensity condition yielded fatigue lives higher than any other peened or unpeened specimens. All specimens at intensity conditions above 0.0030A exhibited fatigue lives below the unpeened control specimen mean.

5.2.5 Aluminum Alloy 7075-T6

Test data were obtained at a maximum stress condition of 58 ksi.

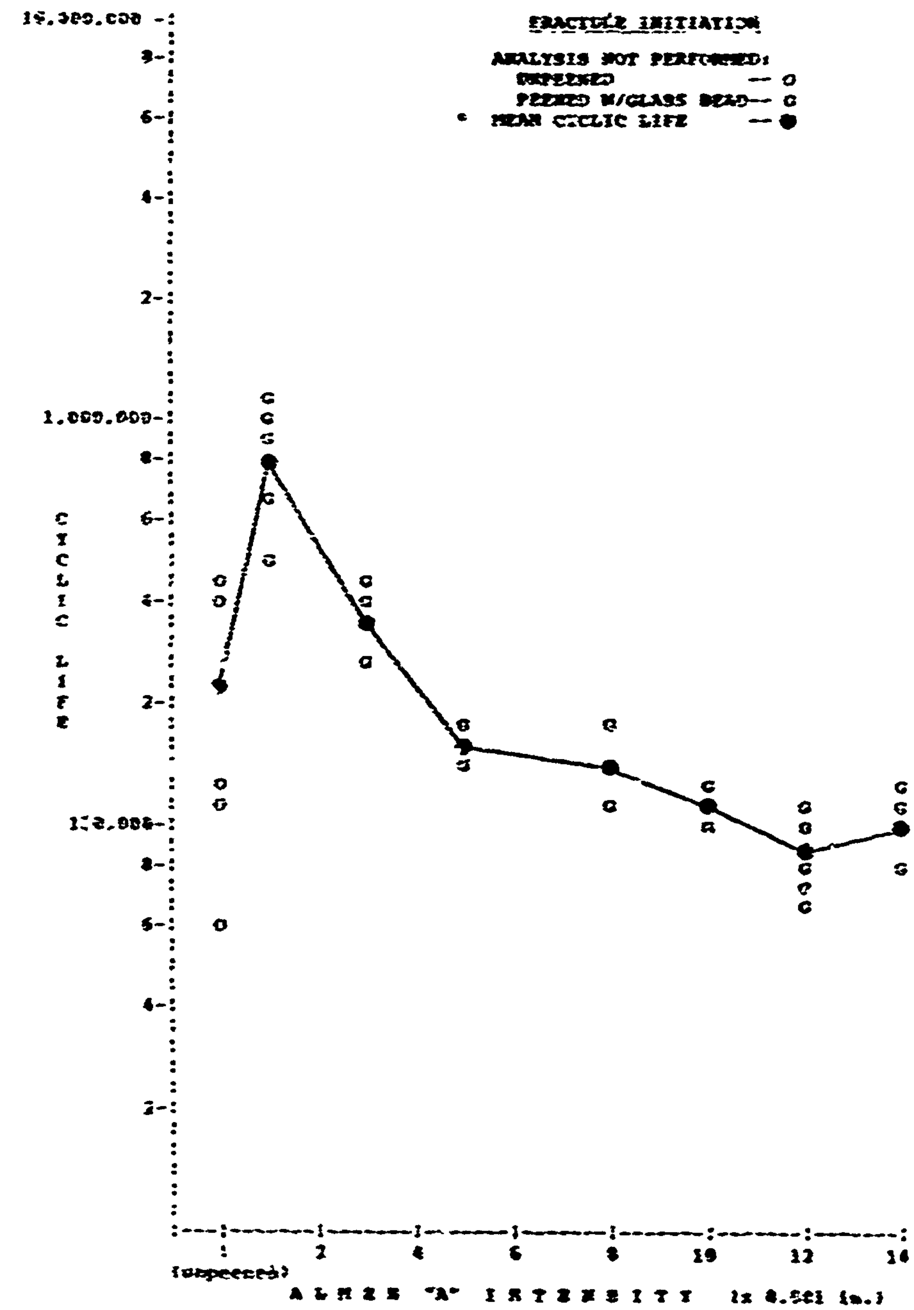


*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

TEST GROUP :	FATIGUE LIFE VERSUS INTENSITY (TASK 2)
MATERIAL :	2024-T4 ALUMINUM 110/119 HBN (LOT C-0001)
SPECIMEN SURFACE :	LATHE TURNED & POLISHED (C)
WORKPIECE SATURATION :	100%
ANGLE OF IMPACT :	90 DEGREES
MAXIMUM STRESS (KSI) :	47

FIGURE 32

FATIGUE RESULTS VS. INTENSITY, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 2024-T4 ALUMINUM



*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT <u>APPENDIX A</u> FOR COMPLETE DATA.

TEST GROUP :	FATIGUE LIFE VERSUS INTENSITY (TASK 2)
MATERIAL :	6061-T6 ALUMINUM 93/100 HBN (LOT C-0003)
SPECIMEN SURFACE :	LATHE TURNED & POLISHED (C)
WORKPIECE SATURATION :	100%
ANGLE OF IMPACT :	90 DEGREES
MAXIMUM STRESS (KSI) :	40

FIGURE 33

FATIGUE RESULTS VS. INTENSITY, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 6061-T6 ALUMINUM

Figure 34 and Table A-6 (Appendix A) present the fatigue life versus Almen intensity data. Figure 35 and Table A-5 (Appendix A) present the fatigue life versus Almen intensity data from Phase I testing for the same material. Note that there was no change in the general pattern of results although the specimen gauge section diameter is reduced by 46.7-percent which results in a duction of cross sectional area of 71.6 percent from Phase I to Phase II.

RESULTS

Unpeened control specimens exhibited a mean fatigue life of 129,000 cycles. Increasing peening intensity above 0.0010A was generally associated with a consistent trend of decreasing fatigue life.

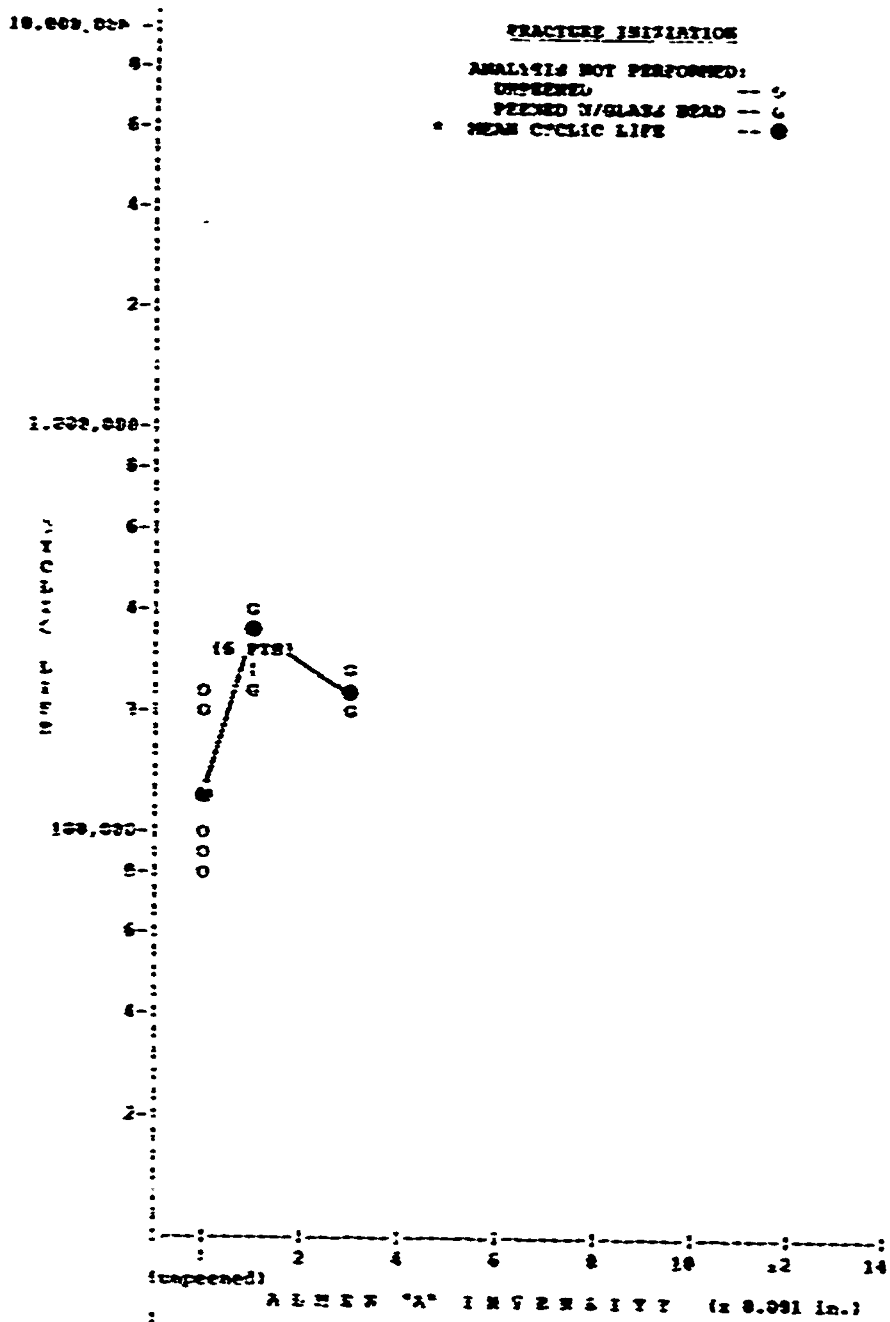
5.2.6 Aluminum Alloy 7075-T73

Test data were obtained at a maximum stress condition of 50 ksi. Figure 36 and Table A-7 (Appendix A) present the fatigue life versus Almen intensity data.

RESULTS

Unpeened control specimens exhibited a mean fatigue life of 66,000 cycles and two parameter Weibull value of 4,373. As peening intensity increased above 0.0020A Weibull fatigue life generally decreased.

Unpeened control specimens exhibited surface fracture initiation sites. All specimens peened at an intensity of 0.0020A exhibited internal fracture initiation. The 0.0040A intensity condition specimens exhibited both internal and external fracture initiation sites. Peening intensities of 0.0060A up to and including 0.00140A produced surface fracture initiation sites in all specimens. In 0.0080A (Figures 46 and 48) through 0.0140A (Figures 37 through 45, and 47) conditions, PSEF were positively identified at the fracture

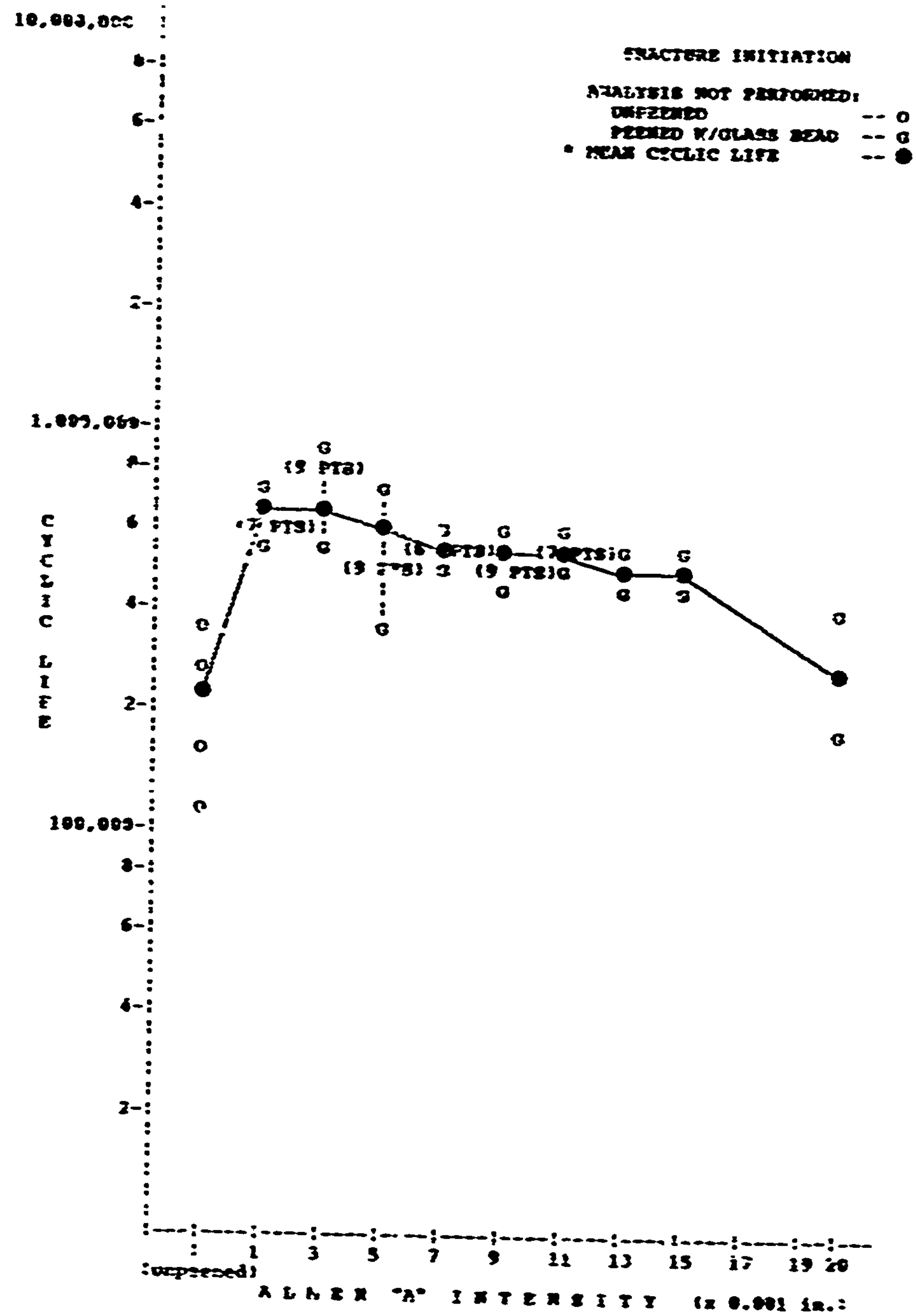


*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

TEST GROUP :	FATIGUE LIFE VERSUS INTENSITY (TASK 2)
MATERIAL :	7075-T6 ALUMINUM 143 HBN (LOT C-0002)
SPECIMEN SURFACE :	LATHE TURNED & POLISHED (C)
WORKPIECE SATURATION :	100%
ANGLE OF IMPACT :	90 DEGREES
MAXIMUM STRESS (KSI) :	58

FIGURE 34

FATIGUE RESULTS VS. INTENSITY, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 7075-T6 ALUMINUM

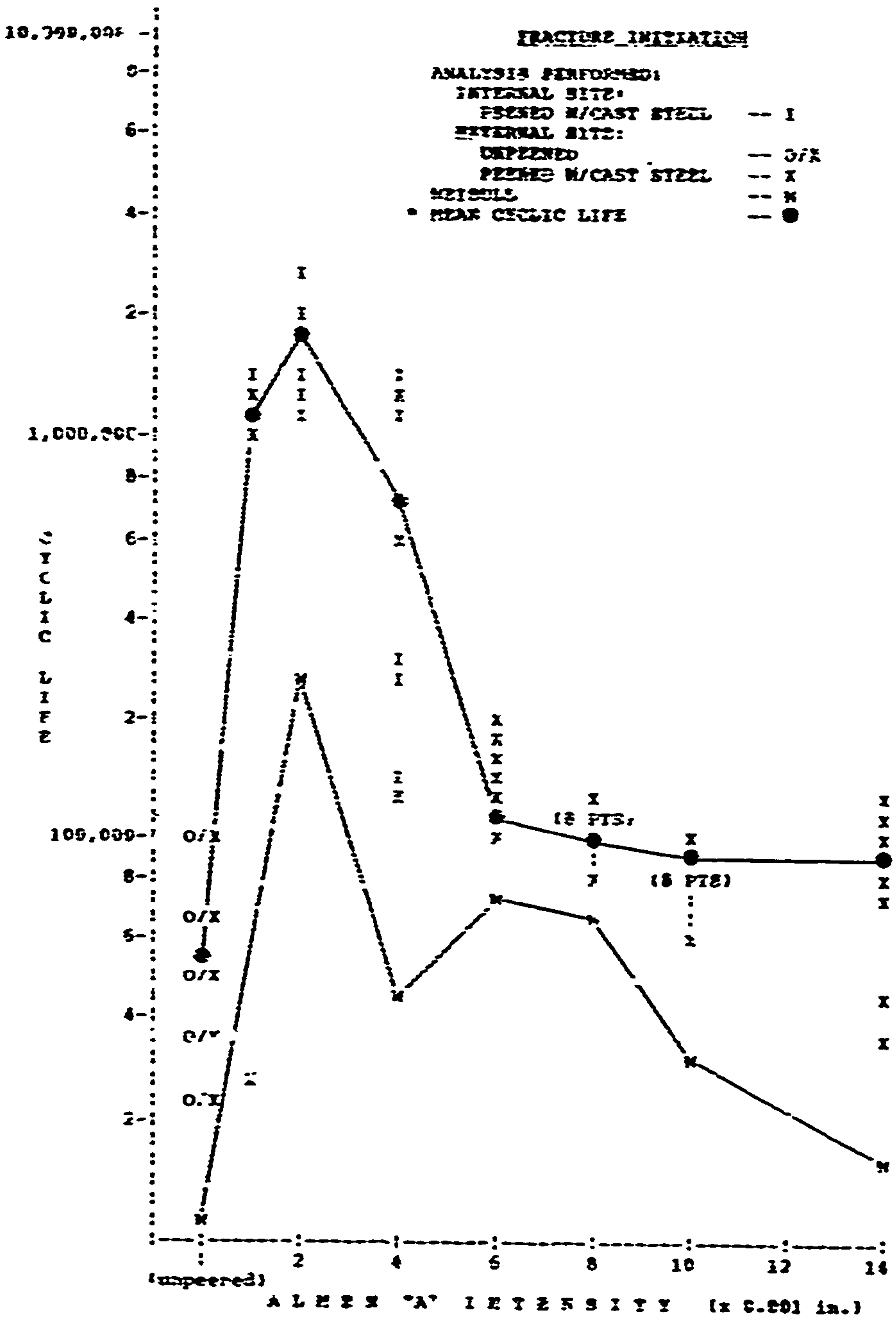


*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

MATERIAL	:	7075-T6
SPECIMEN SURFACE	:	LATHE TURNED AND POLISHED
WORKPIECE SATURATION	:	100%
ANGLE OF IMPACT	:	90 DEGREES
MAXIMUM STRESS (KSI)	:	58 KSI
GAGE SECTION DIA.	:	0.375"

FIGURE 35

FATIGUE RESULTS VERSUS INTENSITY & PEENING PARAMETERS FOR 7075-T6 ALUMINUM PHASE I



*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

TEST GROUP :	FATIGUE LIFE VERSUS INTENSITY (TASK 2)
MATERIAL :	7075-T73 ALUMINUM 136 HBN (LOT C-0030)
SPECIMEN SURFACE :	LATHE TURNED & POLISHED (C)
WORKPIECE SATURATION :	100%
ANGLE OF IMPACT :	90 DEGREES
MAXIMUM STRESS (KSI) :	50

FIGURE 36

FATIGUE RESULTS VS. INTENSITY, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 7075-T73 ALUMINUM

initiation site of 100-percent of specimens examined.

FIGURE 37 7075-T73 ALUM. AT 0.0140A EXTERNAL INITIATION AT PSEF (ARROW DENOTES CRACK INITIATION SITE), 150X

FIGURE 38 - 7075-T73 ALUM. AT 0.0140A AT 200X, EXTERNAL INITIATION AT PSEF

FIGURE 39 - FIGURE 38 AT 350X

FIGURE 40 - FIGURE 38 AT 1000X

FIGURE 41 - FIGURE 38 AT 2000X

FIGURE 42- 7075-T73 ALUM. AT 0.0140A AT 150X, EXTERNAL INITIATION AT PSEF (ARROW DENOTES CRACK INITIATION SITE)

FIGURE 43- FIGURE 42 AT 350X

FIGURE 44- FIGURE 42 AT 1000X

FIGURE 45- FIGURE 42 AT 1970X

FIGURE 46- 7075-T73 ALUM. AT 0.0080A PSEF EVIDENT, 200X

FIGURE 47- 7075-T73 ALUM AT 0.0140A AT 200X, SIGNIFICANT PSEF FORMATION

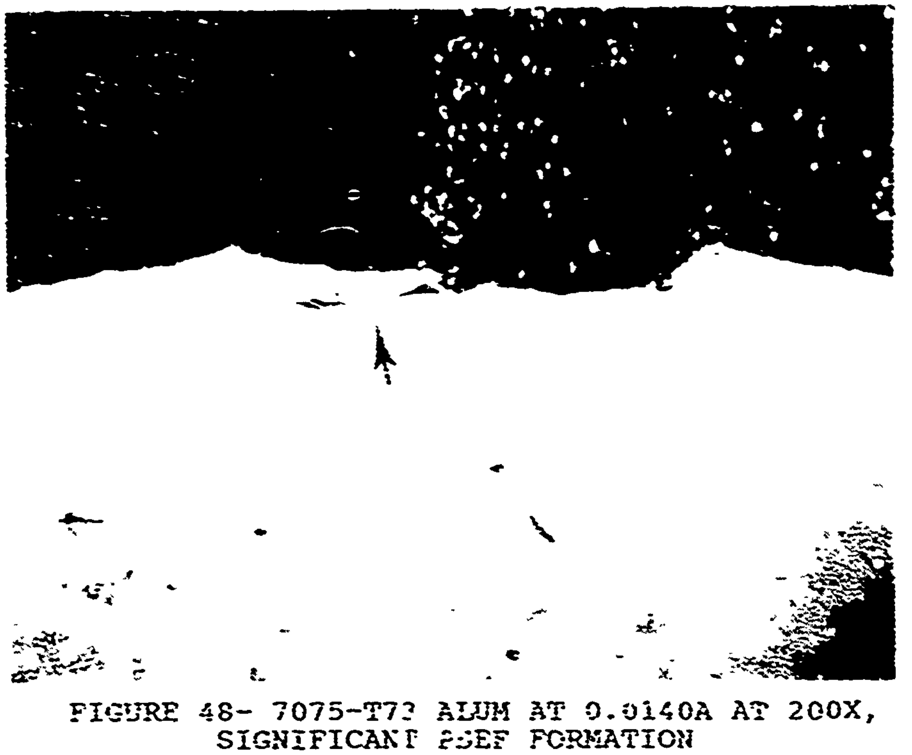


FIGURE 48- 7075-T73 ALUM AT 0.0140A AT 200X, SIGNIFICANT PSEF FORMATION

5.2.7 4340 Alloy Steel - Airmelt - 20/25 HRC

Test data were obtained at a maximum stress condition of 102 ksi. Figure 49 and Table A-8 (Appendix A) present the fatigue life versus intensity data.

RESULTS

Unpeened control specimens exhibited a mean fatigue life of 237,000 cycles. For increasing peening intensities up to and including 0.0040A there was a related increase in mean fatigue life. Except for one specimen, all fracture initiation sites were surface in origin. All fracture initiation sites examined were associated with non metallic inclusions.

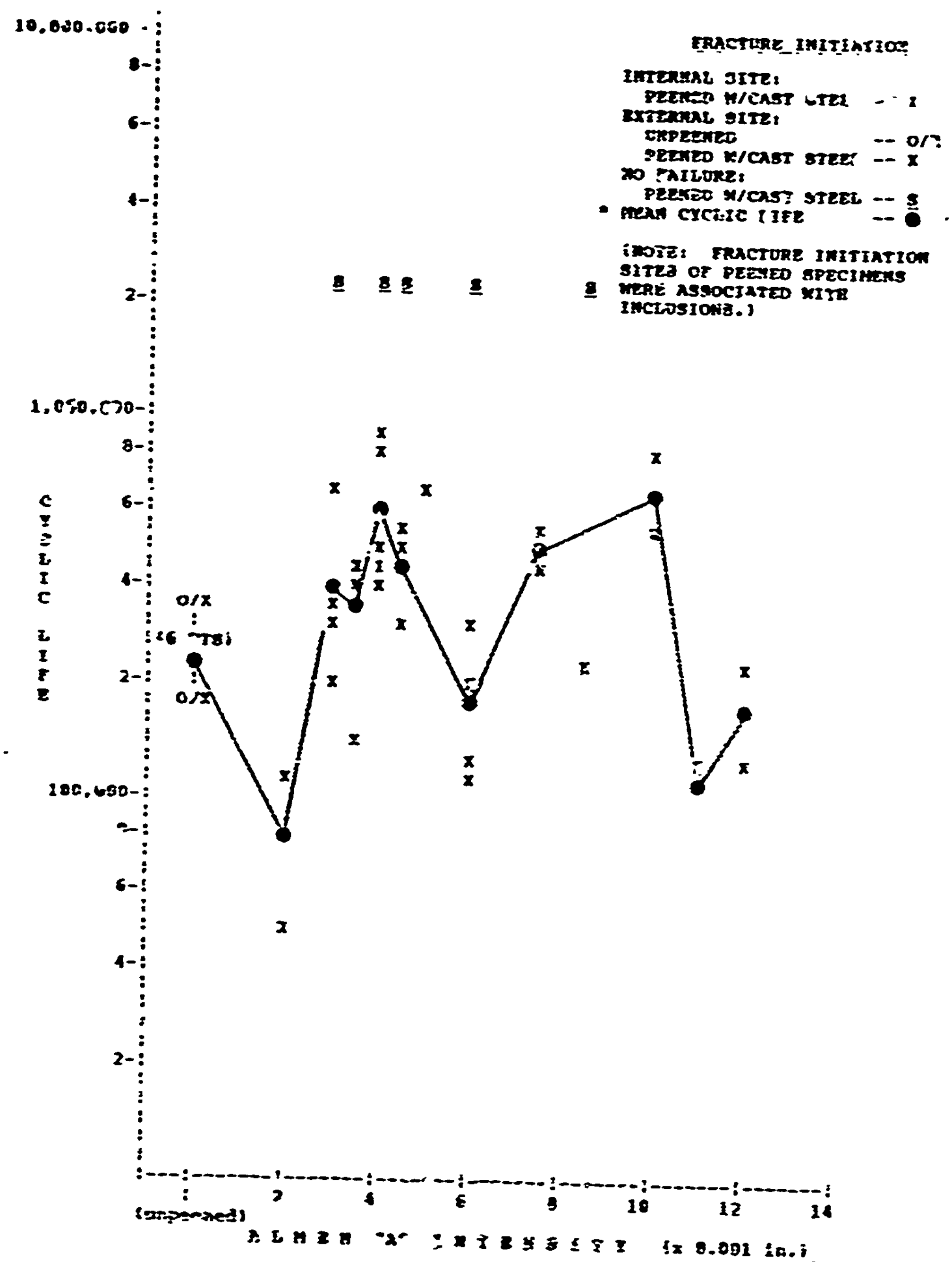
Scatter ranges for all intensity conditions were relatively broad.

5.2.8 4340 Alloy Steel - Airmelt 35/36 HRC

Test data were obtained at a maximum stress condition of 140 ksi. Figure 50 and Table A-9 (Appendix A) present the fatigue life versus intensity data.

RESULTS

Unpeened control specimens exhibited a mean fatigue life of 128,000 cycles. Mean fatigue life of peened specimens generally increases as intensity increases up to the 0.0060A intensity condition and then generally deteriorates through the 0.0120A intensity condition as intensity increases, although this pattern is less than distinct. All fracture initiation sites examined were associated with non metallic inclusions. High fatigue life specimens peened at 0.0045A, 0.0050A, and 0.0060A intensities exhibited internal fracture initiation as compared to all other test specimens exhibiting surface fracture initiation sites. All specimen fatigue lives in 0.0040A,

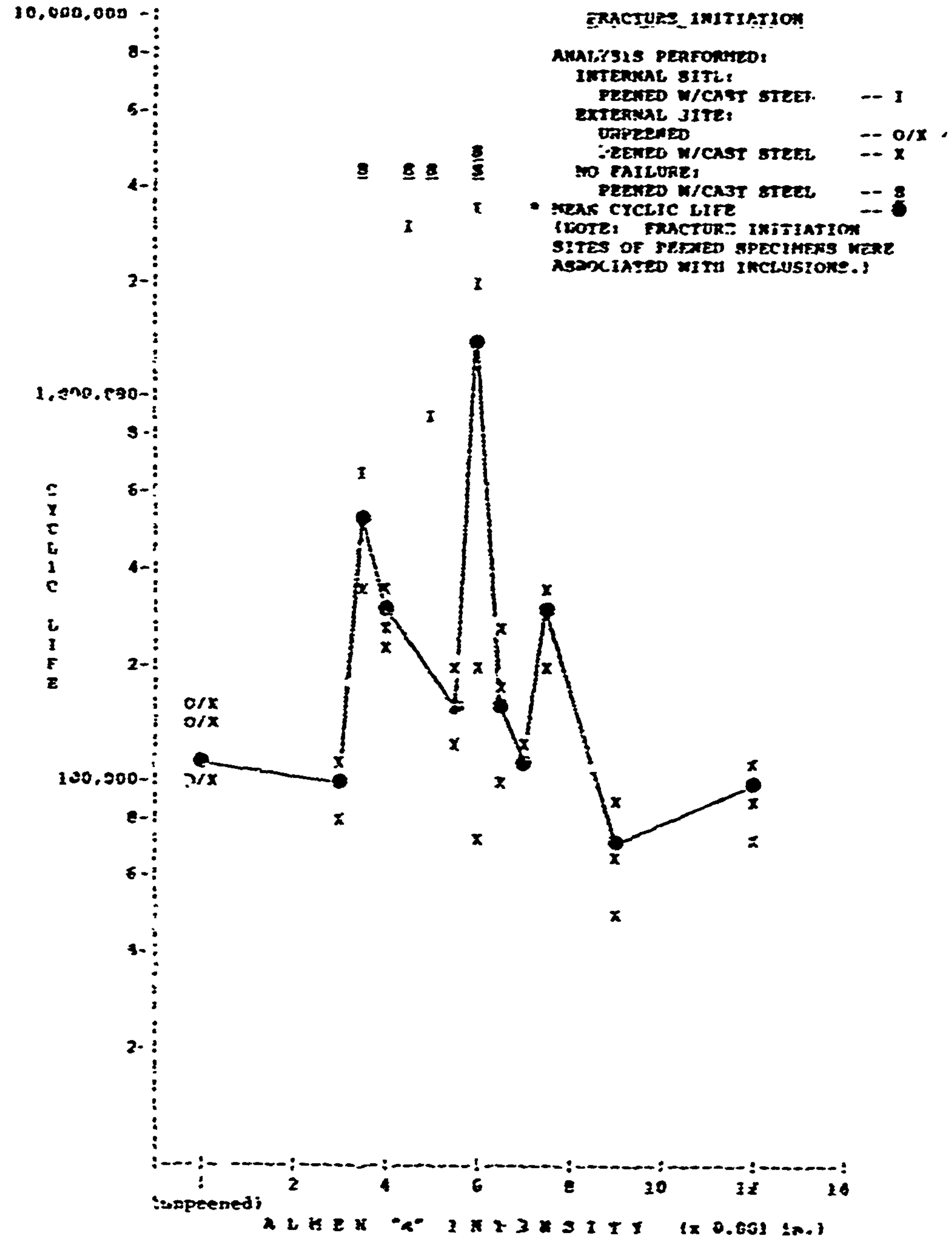


*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

TEST GROUP :	FATIGUE LIFE VERSUS INTENSITY (TASK 2)
MATERIAL :	4340 AIRMELT STEEL 20/25 HRC (LOT C-0006)
SPECIMEN SURFACE :	GROUND AND POLISHED (C)
WORKPIECE SATURATION :	100%
ANGLE OF IMPACT :	90 DEGREES
MAXIMUM STRESS (KSI) :	102

FIGURE 49

FATIGUE RESULTS VS. INTENSITY. PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 4340 AIRMELT STEEL 20/25 HRC



*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

TEST GROUP	:	FATIGUE LIFE VERSUS INTENSITY (TASK 2)
MATERIAL	:	4340 AIRMELT STEEL 34/36 HRC (LOT C-0007)
SPECIMEN SURFACE	:	GROUND & POLISHED (L)
WORKPIECE SATURATION	:	100%
ANGLE OF IMPACT	:	90 DEGREES
MAXIMUM STRESS (KSI)	:	140

FIGURE 50

FATIGUE RESULTS VERSUS INTENSITY, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 4340 AIRMELT STEEL 34/36 HRC

0.0045A, and 0.0050A intensity conditions were above the fatigue lives of all specimens with intensity conditions greater than 0.0070A.

5.2.9 4340 Alloy Steel - Airmelt - 40/42 HRC

The test data were obtained at a maximum stress condition of 155 ksi. Figure 51 and Table A-10 (Appendix A) present the fatigue life versus intensity data.

RESULTS

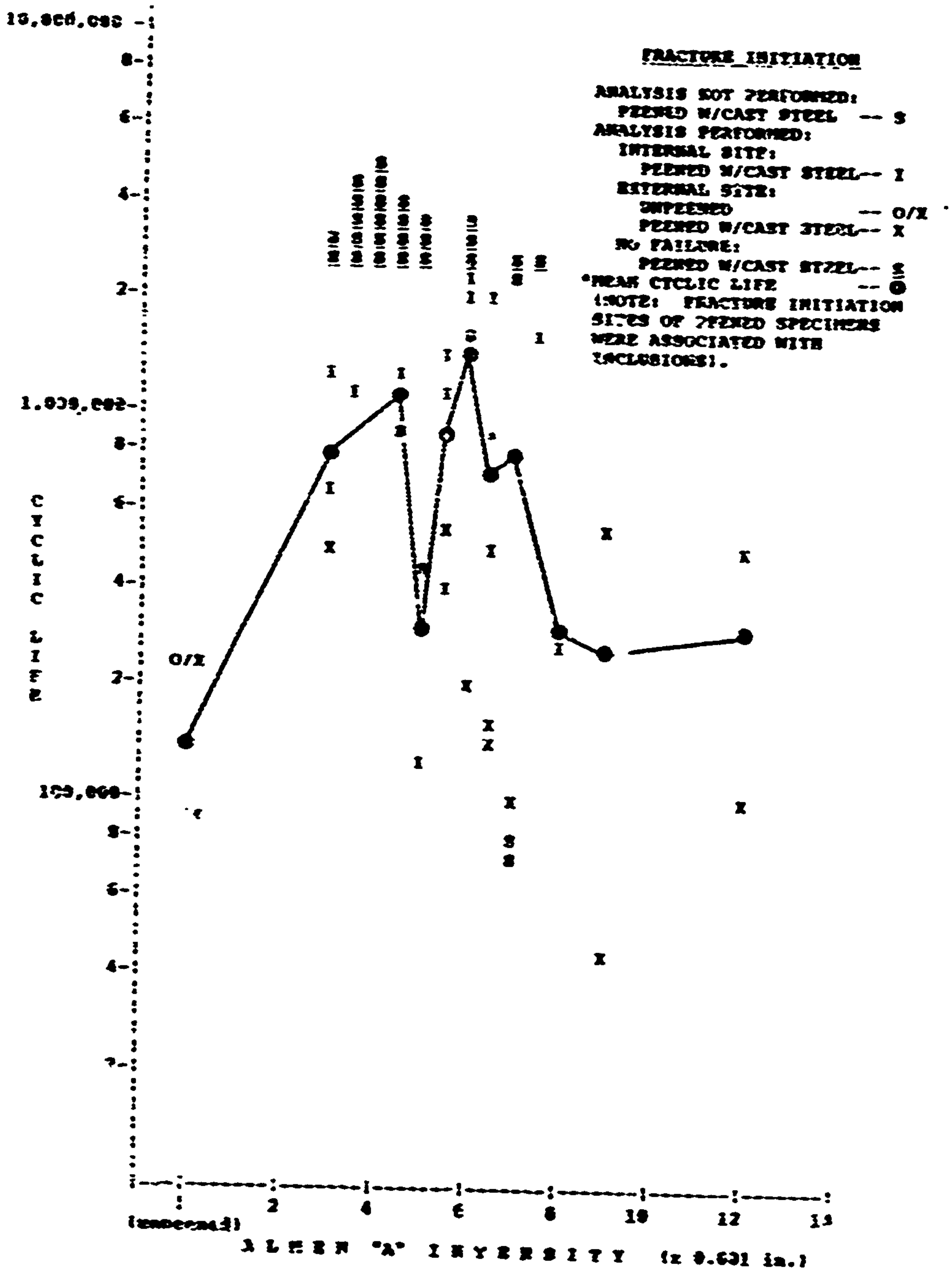
Unpeened control specimens exhibited a mean fatigue life of 159,000 cycles. Fatigue life increased with intensity for specimens peened at 0.0030A, 0.0035A, and 0.0040A intensities. One hundred percent of the fracture initiation sites for specimens examined in the 0.0030A, 0.0035A, 0.0040A, and 0.0045A conditions were internal in origin and associated with non metallic inclusions. Mean fatigue life peaked at 1,467,000 in the 0.0060A condition. Mean fatigue life for specimens peened above 0.006A generally decreased through the 0.0120A intensity condition. One hundred percent of specimens peened at intensities of 0.0090A or greater exhibited fracture initiation sites that originated at the surface.

5.2.10 4340 Alloy Steel - Airmelt - 48/50 HRC

Test data were obtained at a maximum stress condition of 170 ksi. Figure 52 and Table A-11 (Appendix A) present the fatigue life versus Almen intensity data.

RESULTS

Unpeened control specimens exhibited a mean fatigue life of 74,000 cycles. Fatigue life was above unpeened at all intensity conditions. Inclusions were associated with fracture initiation sites in all but three of the specimens examined. Scanning electron microscope X-ray probe analysis confirmed the foreign inclusions present were aluminum oxide.

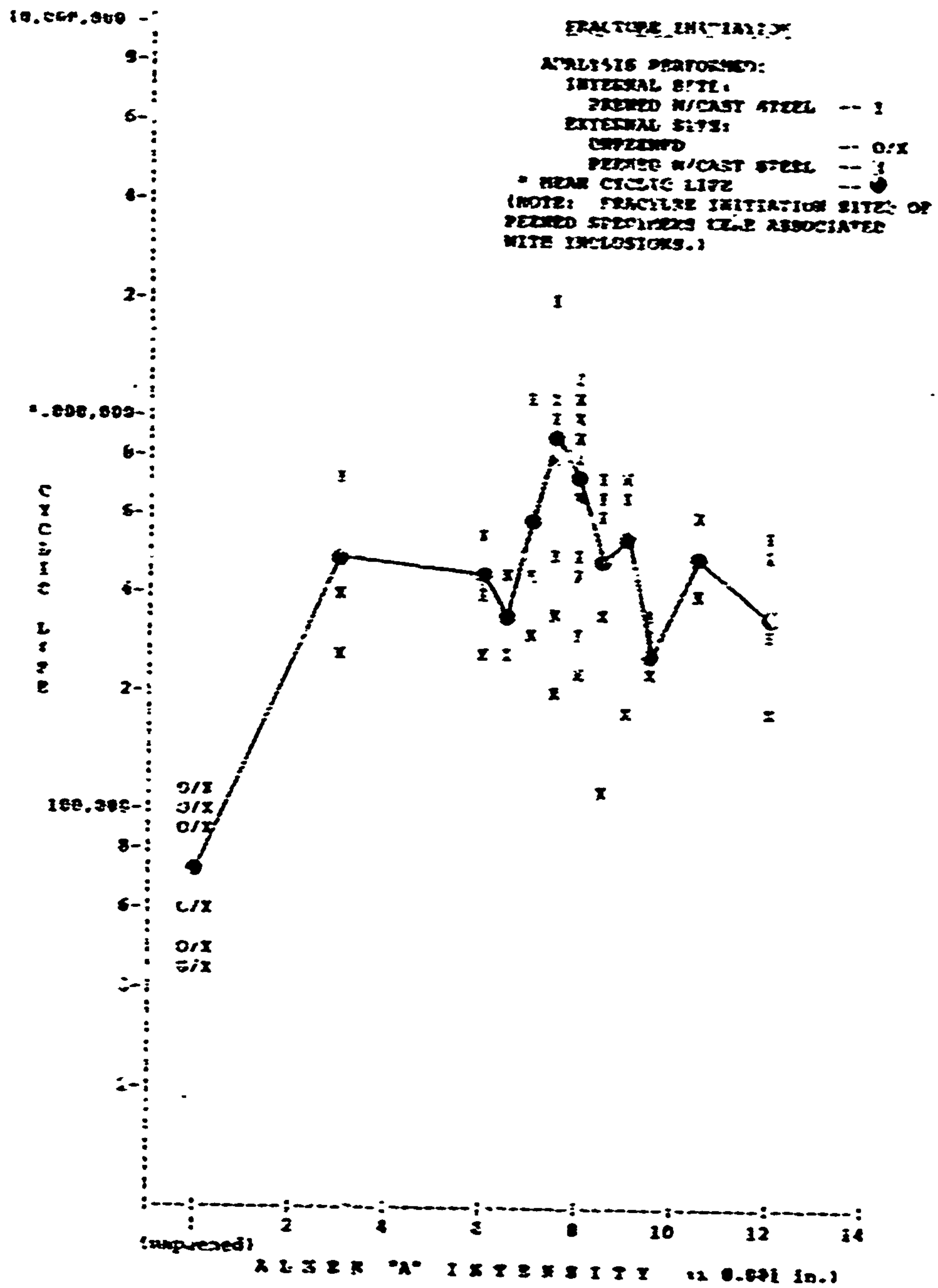


*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

TEST GROUP :	FATIGUE LIFE VERSUS INTENSITY (TASK 2)
MATERIAL :	4340 AIRMELT STEEL, 40/42 HRC (LOT C-0020)
SPECIMEN SURFACE :	GROUND & POLISHED (L)
WORKPIECE SATURATION :	100%
ANGLE OF IMPACT :	90 DEGREES
MAXIMUM STRESS (KSI) :	155

FIGURE 51

FATIGUE RESULTS VERSUS INTENSITY, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 4340 AIRMELT STEEL 40/42 HRC



*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

TEST GROUP :	FATIGUE LIFE VERSUS INTENSITY (TASK 2)
MATERIAL :	4340 AIRMELT STEEL 48/50 HRC (LOT C-0021)
SPECIMEN SURFACE :	GROUND AND POLISHED (L)
WORKPIECE SATURATION :	100%
ANGLE OF IMPACT :	90 DEGREES
MAXIMUM STRESS (KSI) :	170

FIGURE 52

FATIGUE RESULTS VERSUS INTENSITY, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 4340 AIRMELT STEEL 48/50 HRC

Figure 53 shows specimen 0797 peened at 0.0080A intensity exhibiting a subsurface fracture initiating at a foreign inclusion at 100X magnification.

Figure 55 shows specimen 0818 peening at 0.0080A intensity exhibiting an internal primary fracture site at a foreign inclusion at 100X magnification. The intensity conditions of 0.0070A through 0.0090A exhibit both higher peak fatigue life and a greater fatigue strength in the surface as witnessed by a higher percentage of internal primary failure sites. This is believed, however, to be more a factor of the particular inclusions in the specimens of these conditions than of the peening condition as scatter in all conditions was relatively broad.

The identification of an Optimum Intensity Range is as such, clouded considerably by the presence of non metallic inclusions and the relatively large fatigue life scatter associated with their presence (Figures 53 through 56).

5.2.11 4340 Alloy Steel - Vacuum Arc Remelt - 48/50 HRC

Test data were obtained at a maximum stress condition of 195 ksi. Figure 57 and Table A-12 (Appendix A) present the fatigue life versus Almen intensity data.

Unpeened control specimens exhibited a mean fatigue life of 41,000 cycles and Weibull fatigue life of 7000 cycles. Mean fatigue life and Weibull fatigue life were 1,359,000 cycles and 267,000 cycles respectively in the 0.0020A condition. Increasing peening intensity above 0.0020A was associated with a consistent downward trend in specimen mean and Weibull fatigue life.

FIGURE 53- 4340 AIRMELT STEEL 48/50 HRC AT 0.0080A AT 100X, EXTERNAL INITIATION, INCLUSION PRESENT

FIGURE 54- FIGURE 53 AT 1000X (ALUMINUM OXIDE PARTICLE)

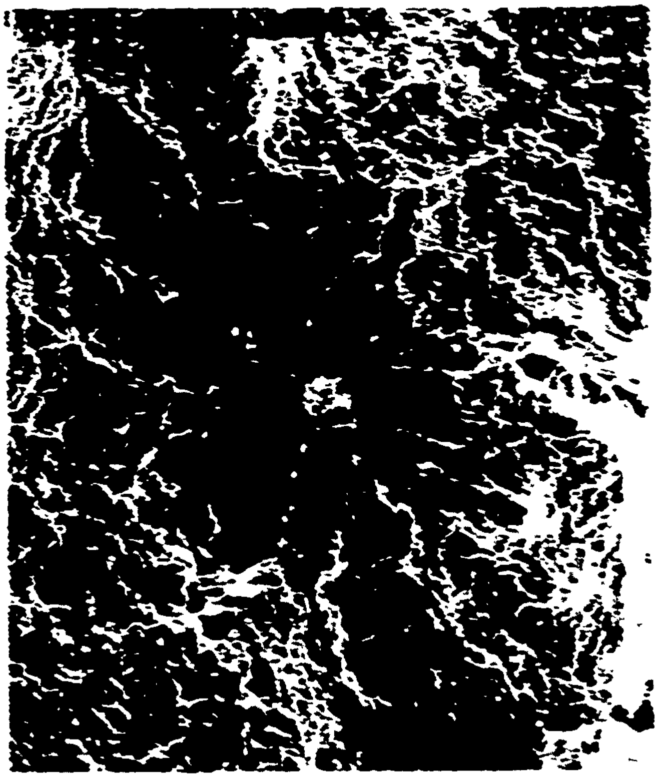
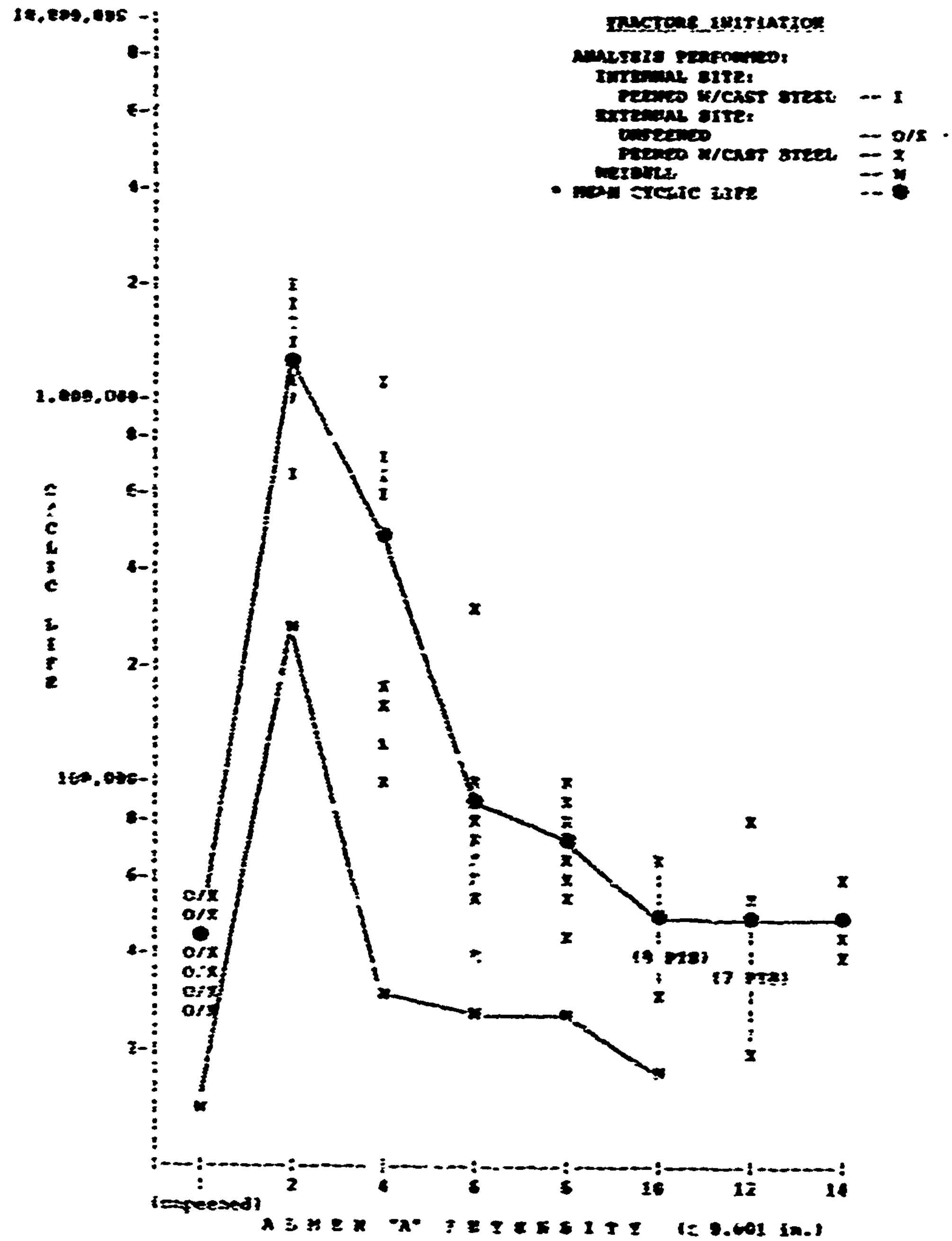


FIGURE 55- 4340 AIRMELT STEEL 48/50 HRC AT 0.0080A AT 100X, INTERNAL INITIATION AT INCLUSION

FIGURE 56- FIGURE 55 AT 1000X (ALUMINUM OXIDE PARTICLE)



*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

TEST GROUP :	FATIGUE LIFE VERSUS INTENSITY (TASK 2)
MATERIAL :	4340 VACUUM ARC REMELT STEEL 48/50 HRC (LOT C-0028)
SPECIMEN SURFACE :	GROUND
WORKPIECE SATURATION :	100%
ANGLE OF IMPACT :	90 DEGREES
MAXIMUM STRESS (KSI) :	195

FIGURE 57

FATIGUE RESULTS VERSUS INTENSITY, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 4340 VACUUM ARC REMELT STEEL 48/50 HRC

Fracture intiation sites of specimens peened at 0.0020A were internal in origin. Plastic deformation of the surface due to peening did not obliterate the grind marks (Figure 58). Specimens peened at the 0.0040A intensity condition exhibited both internal and external fracture initiation sites, with all internal crack nucleation specimens having a fatigue life above 500,000 cycles and all external crack nucleation site specimens having fatigue lives below 200,000 cycles. At peening intensity conditions above 0.0040A fracture initiation sites are exclusively external. Specimens peened at 0.0080A exhibited PSEF formation (Figure 59). Specimens peened at 0.0140A exhibited exaggerated PSEF formation (Figures 60 and 61).

5.2.12 Stress versus Cycles to Failure (S/N Study)

S/N curves were established for the following materials:

(1) Aluminum 7075-T73.
(2) AISI 4340 Steel, Airmelt, 48/50 HRC.
(3) AISI 4340 Steel, Vacuum Arc Remelt, 48/50 HRC.

5.2.12.1 7075-T73 Aluminum Alloy

Specimens were peened at 0.0020A Almen intensity (per Task 2) at 100-percent workpiece saturation (Per Task 1). Test data were incrementally obtained at maximum stress conditions ranging from 80-percent up to and including 120-percent of the maximum stress condition (50 ksi) used in the fatigue life versus intensity task.

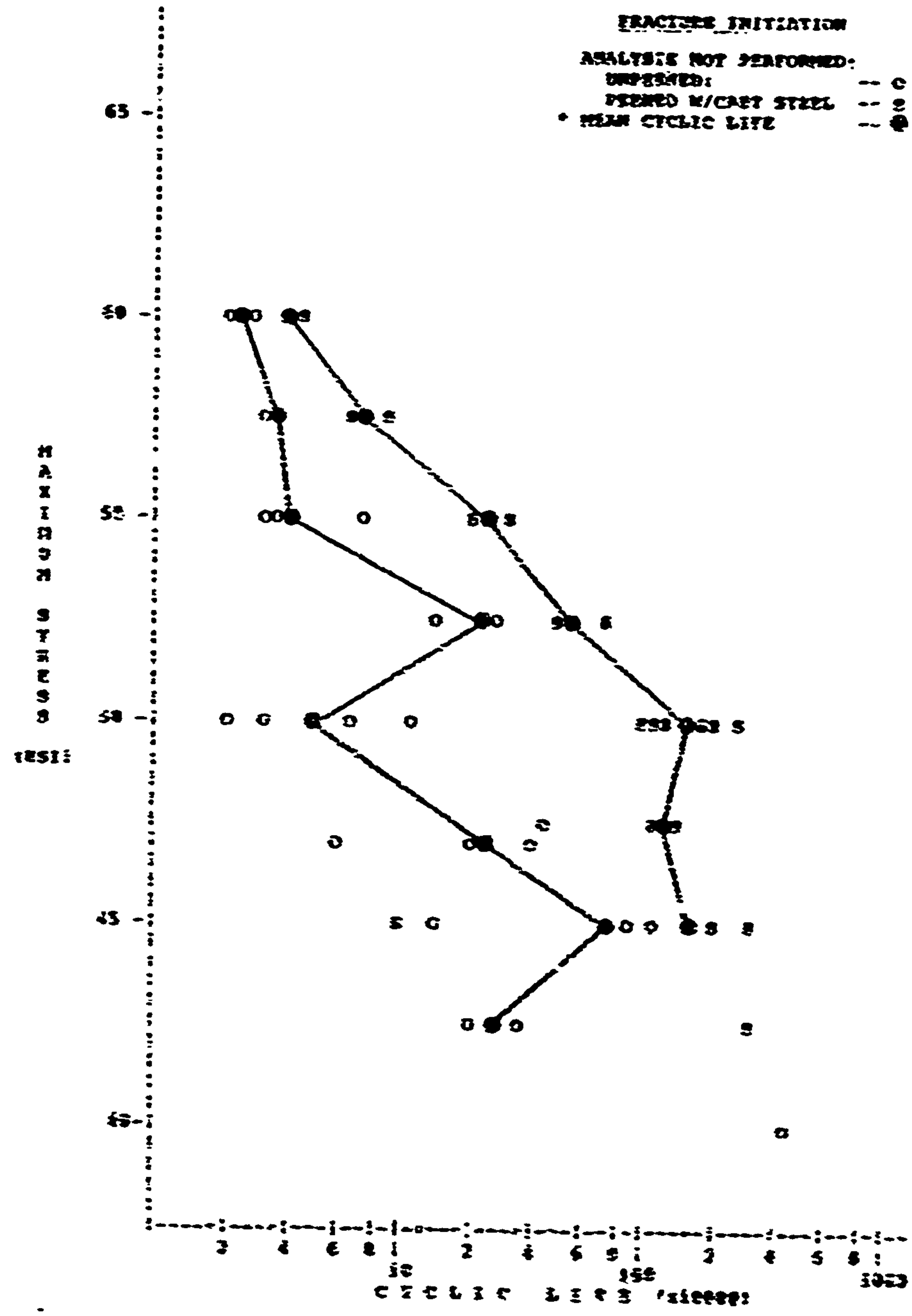
Figure 62 and Table A-13 (Appendix A) present the S/N data. Fatigue limit for this material (stress level at which failure does not occur) was not defined. The data clearly show, however, that peening resulted in significantly improved fatigue life at all stress levels employed in testing.

FIGURE 58- 4340 STEEL VAR 48/50 HRC AT 0.0020A AT 200X, TOOL MARKS PRESENT

FIGURE 59- 4340 STEEL VAR 48/50 HRC AT 0.0080A AT 200X, PSEF AND TOOL MARKS PRESENT

FIGURE 60- 4340 STEEL VAR 48/50 HRC AT 0.0140A AT 350X, PSEF AND TOOL MARKS PRESENT

FIGURE 61- 4340 STEEL VAR 48/50 HRC AT 0.0140A AT 800X, PSEF PRESENT (CROSS SECTION)



*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

TEST GROUP :	FATIGUE LIFE VERSUS STRESS (TASK 2 - S/N)
MATERIAL :	7075-T73 ALUMINUM 136 HBN (LOT C-0030)
SPECIMEN SURFACE :	LATHE TURNED & POLISHED (C)
ALMEN INTENSITY :	0.002CA (OPTIMUM PER TASK 2)
WORKPIECE SATURATION :	100% (OPTIMUM PER TASK 4)
MEDIA SIZE/TYPE :	S-70 CAST STEEL
ANGLE OF IMPACT :	90 DEGREES

FIGURE 62

FATIGUE RESULTS VS. STRESS, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 7075-T73 ALUMINUM

5.2.12.2 4340 Alloy Steel - Airmelt 48/50 HRC

Specimens were peened at 0.0080A (Per Task 2) at 100-percent workpiece saturation (Per Task 1). Test data were obtained incrementally at maximum stress conditions ranging from 85-percent up to and including 125-percent of the maximum stress condition (170 ksi) used in the fatigue life versus intensity task.

Figure 63 and Table A-14 (Appendix A) present the S/N data. Fatigue limit maximum stress condition of the peened specimens was defined as 161.5 ksi. Fatigue limit of the unpeened control specimen was defined as 144.5 ksi. The increase in the fatigue limit of this material to be realized through peening at a 0.0080A intensity condition over the unpeened condition was 17 ksi, or 10.5-percent. Mean fatigue life was significantly improved by peening for all stress levels employed in testing.

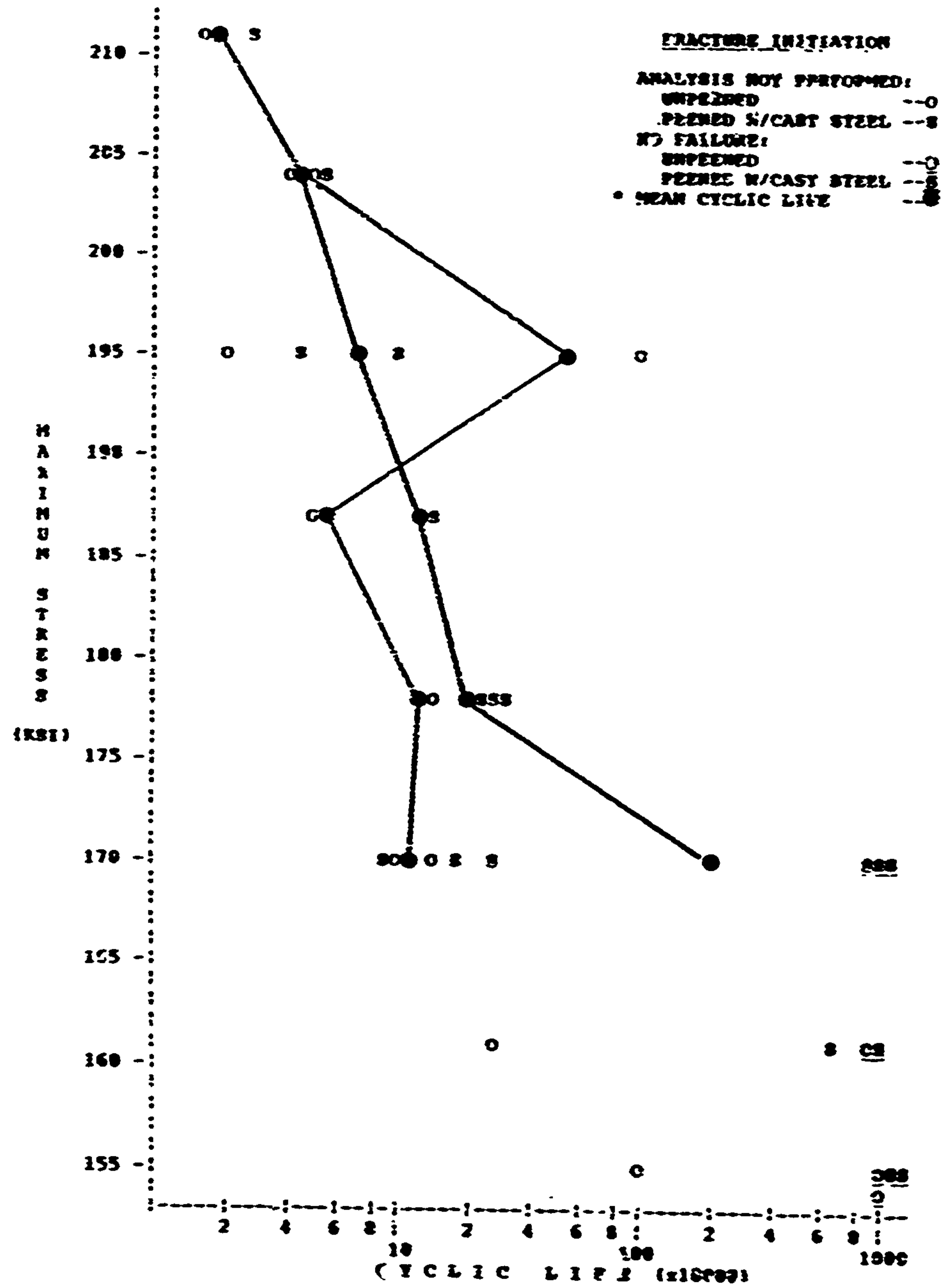
5.2.12.3 4340 Alloy Steel - Vacuum Arc Remelt - 48/50 HRC

Specimens were peened at 0.0020A (Per Task 2) at 100-percent workpiece saturation (Per Task 1). Test data were obtained at increasing stress conditions in increments from 84-percent up to 110-percent of the maximum stress condition (195 ksi) used in the fatigue life versus intensity test group (Per Task 2).

Figure 64 and Table A-15 (Appendix A) present the S/N data. Fatigue limit for this material was not defined. Mean fatigue life at each stress level employed for testing was significantly improved by peening.

5.3 TASK 3 : THE EFFECT OF INITIAL SURFACE CONDITION ON FATIGUE LIFE AFTER SHOT PEENING

All results presented in the Task 2 represented specimens with gauge sections machined and mechanically polished prior to peening. Task 3 was performed to determine if fatigue life and/or optimum

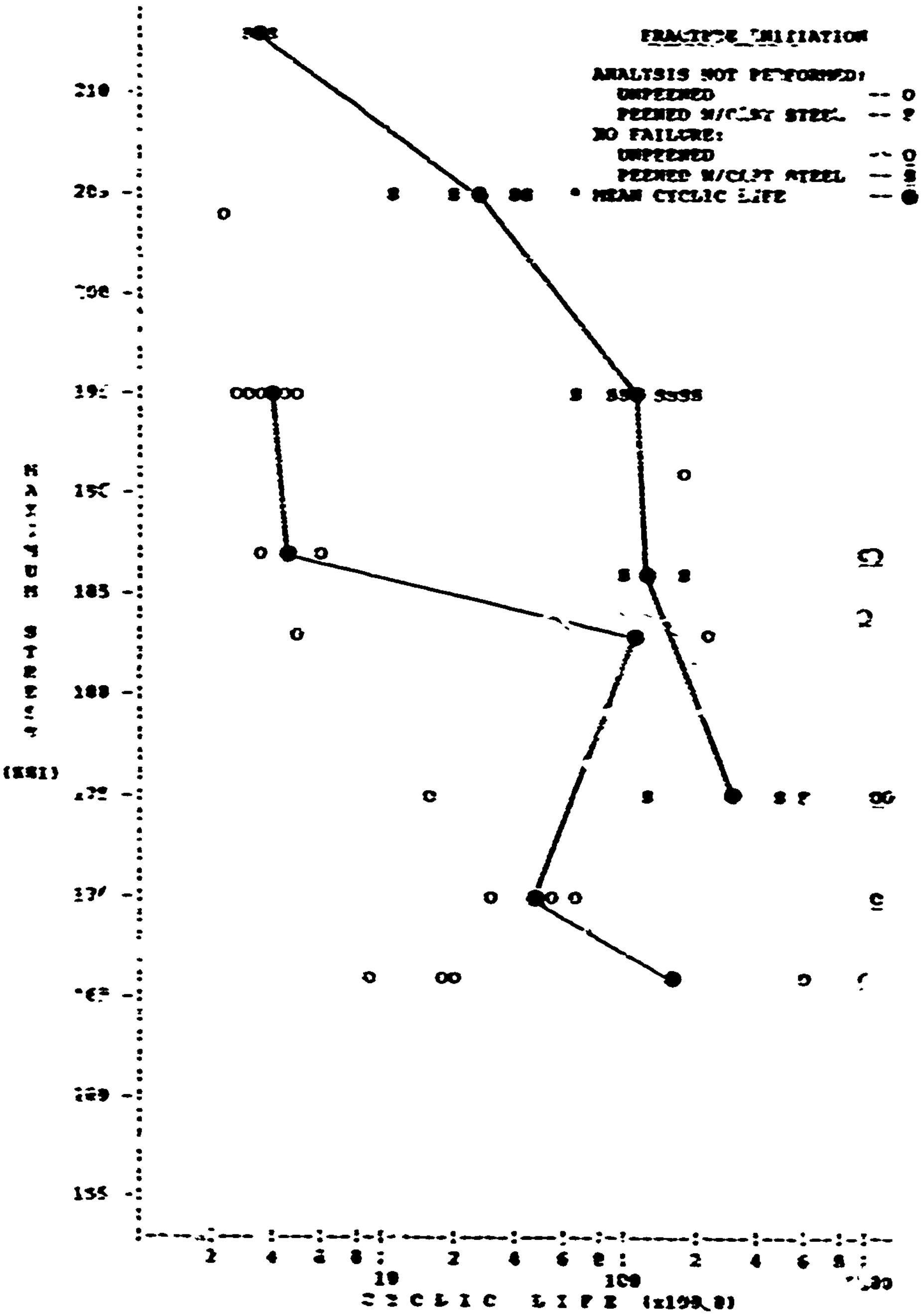


*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

TEST GROUP :	FATIGUE LIFE VERSUS STRESS (TASK 2 - S/N)
MATERIAL :	4340 AIRMELT STEEL 48/50 HRC (LOT C-0025)
SPECIMEN SURFACE :	GROUND & POLISHED
ALMEN INTENSITY :	0.0080A (OPTIMUM PER TASK 2)
WORKPIECE SATURATION :	100% (OPTIMUM PER TASK 4)
MEDIA SIZE/TYPE :	S-70 CAST STEEL
ANGLE OF IMPACT :	90 DEGREES

FIGURE C3

FATIGUE RESULTS VS. STRESS, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 4340 AIRMELT STEEL 48/50 HRC



*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

TEST GROUP :	FATIGUE LIFE VERSUS STRESS (TASK 2 - S/N)
MATERIAL :	4340 VACUUM ARC REMELT STEEL 48/50 HRC
SPECIMEN SURFACE :	GROUND
ALMEN INTENSITY :	0.0020A (OPTIMUM PER TASK 2)
WORKPIECE SATURATION :	100% (OPTIMUM PER TASK 4)
MEDIA SIZE/TYPE :	S-70 CAST STEEL
ANGLE OF IMPACT :	90 DEGREES

FIGURE 61

FATIGUE RESULTS VS. STRESS, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 4340 VACUUM ARC REMELT STEEL 48/50 HRC

intensity range would be affected by the initial surface condition. The scope was limited to 7075-T6 Aluminum specimens with lathe turned (no mechanical polishing) gauge sections. The data were compared against Task 2 data.

5.3.1 Aluminum Alloy 7075-T6 -- Lathe Turned Only

Additional test samples were evaluated in the lathe turned only pre peening surface condition at peening intensity conditions of 0.0020A, 0.0040A, 0.0060A and 0.0080A as well as unpeened control. The prepeening specimen surface finish, approximately 60 RMS, was a threefold increase compared to the lathe turned and polished specimen surface condition (Figure 6).

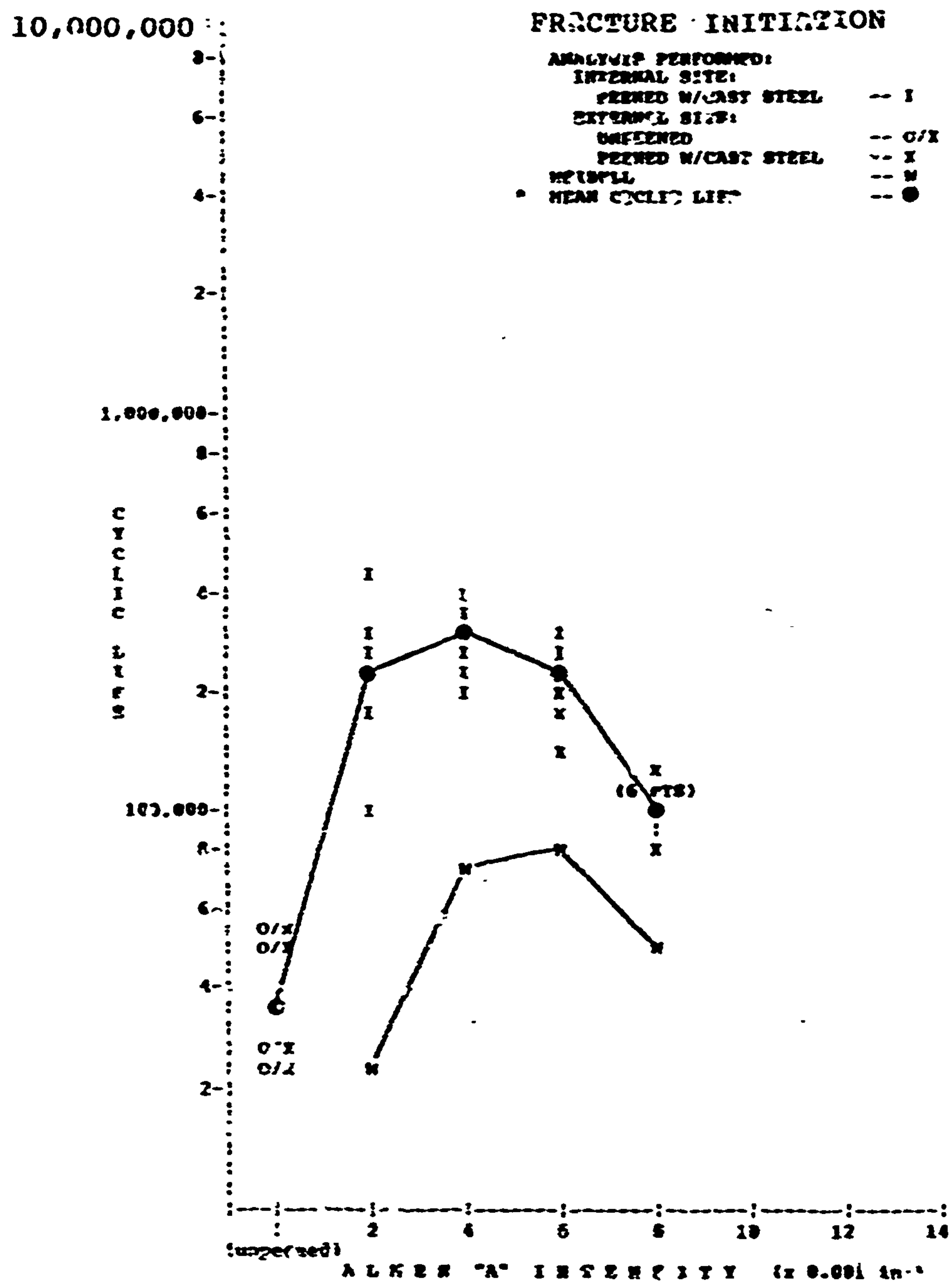
As with lathe turned and polished 7075-T6 specimens, the test data were again obtained at a maximum stress condition of 58 ksi.

Figure 65 and Table A-16 (Appendix A) present the fatigue life versus Almen intensity data. Unpeened control specimens exhibited a mean fatigue life of 39,000 cycles. Weibull fatigue life rose with Almen intensity as intensity increased up to and including 0.0060A.

Specimen failure analysis indicated that at 0.0020A intensity (Figure 66), fracture initiation was internal in origin. The shot peen process induced surface plastic deformation did not obliterate the tool marks (Figure 68). At 0.0040A intensity, the induced surface damage obliterated the tool marks and fracture initiation was internal. At 0.0060A intensity (PSEF present) fracture initiation sites were both internal (Figure 67) and external (Figure 69).

5.4 TASK 4 -- DEFINITION OF THE RELATIONSHIP BETWEEN FATIGUE LIFE AND WORKPIECE SATURATION

Assuming Almen intensity is kept within the optimum intensity range for a given workpiece, then determining the optimum duration of cold working at this energy transfer level is a logical next step. By



*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

TEST GROUP :	FATIGUE LIFE VERSUS INTENSITY (TASK 3)
MATERIAL :	7075-T6 ALUMINUM 143 HBN (LOT C-0002)
SPECIMEN SURFACE :	LATHE TURNED
WORKPIECE SATURATION :	100%
ANGLE OF IMPACT :	90 DEGREES
MAXIMUM STRESS (KSI) :	58

FIGURE 65

FATIGUE RESULTS VS. INTENSITY VS. PREPEENING SURFACE CONDITION, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 7075-T6 ALUMINUM

FIGURE 66- 7075-T6 ALUM AT 0.0020A
AT 35X, INTERNAL INITIATION

FIGURE 67- 7075-T6 ALUM AT 0.0060A
AT 50X, INTERNAL INITIATION

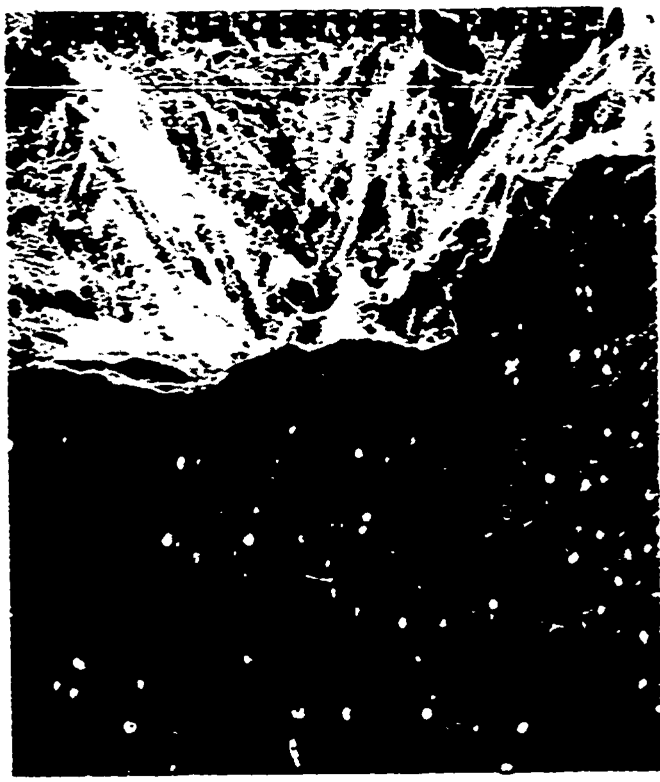


FIGURE 68- 7075-T6 ALUM AT 0.0020A
AT 50X, TOOL MARKS PRESENT, EXTERNAL
INITIATION

FIGURE 69- 7075-T6 ALUM AT 0.0060A
AT 20X, TOOL MARKS NOT PRESENT.
EXTERNAL INITIATION

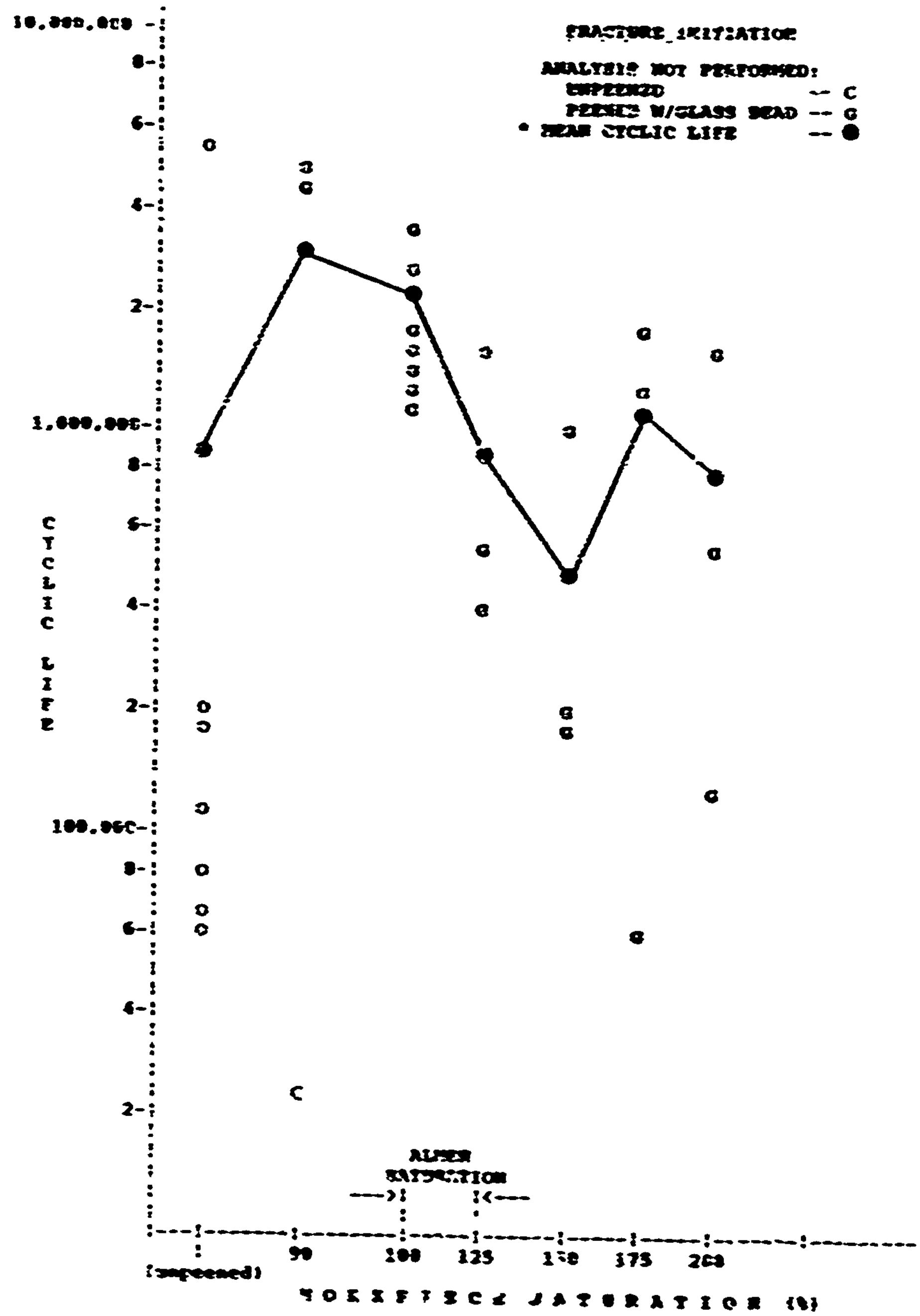
exposing specimens to varying levels of workpiece saturation (as defined by Task 1 results) from 80-percent to some multiple of 100-percent workpiece saturation, definition of whether an optimum saturation level or range exists for the particular workpiece was accomplished. Since Almen test strips range in hardness from 44 to 50 HRC, the point in cycle time at which actual workpiece saturation occurs is a range of Almen saturation reflecting the inherent allowable hardness tolerances in Almen strips. It should be noted that Phase II testing used 45 HRC +/-1 HRC tolerance Almen strips. See Table 2. The range that is exhibited on each cyclic life versus workpiece saturation graph as a function of strip hardness variances is based on the acceptable hardness tolerance range in MIL-S-13165B. Experimental test data generated is plotted as fatigue life versus percentage workpiece saturation.

5.4.1 Ti 6Al - 4V alloy

Figure 70 and Table A-17 (appendix A) present the data for fatigue life versus workpiece saturation on Ti 6Al-4V. Specimens were peened in increments of workpiece saturation from 90-percent through 110-percent and in larger increments from 110-percent to 200- percent. Test data were obtained at a maximum stress condition of 140 ksi.

RESULTS

90-percent workpiece saturation, while exhibiting the highest specimen fatigue lives also exhibited the lowest. 110-percent workpiece saturation had the highest mean fatigue life and the lowest scatter of any saturation condition, even though more specimens were tested in this condition than any other. Mean fatigue life decreased as workpiece saturation increased above 110-percent workpiece



*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

TEST GROUP	:	FATIGUE LIFE VERSUS WORKPIECE SATURATION (TASK 4)
MATERIAL	:	6AL-4V TITANIUM 41/42 HRC (LOT C-0015)
SPECIMEN SURFACE	:	LATHE TURNED AND POLISHED (C)
ALMEN INTENSITY	:	0.0020A (OPTIMUM PER TASK 2)
MEDIA SIZE/TYPE	:	MIL-13 GLASS BEAD
ANGLE OF IMPACT	:	90 DEGREES
MAXIMUM STRESS (KSI)	:	140

FIGURE 70

FATIGUE RESULTS VS. WORKPIECE SATURATION, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION OF TITANIUM 6AL-4V

saturation. Note that the range of Almen saturation which occurs in this material is approximately 100- to 125-percent of workpiece saturation.

5.4.2 2024-T4 Aluminum Alloy

Figure 71 and Table A-18 (Appendix A) present the data for fatigue life versus workpiece saturation. Specimens were peened in increments of workpiece saturation ranging from 80-percent through 400-percent. The test data were obtained at a maximum stress of 47 ksi.

RESULTS

Workpiece saturation showed the highest fatigue life at 100-percent to 200-percent. Fatigue life decreased as saturation was increased above 200-percent workpiece saturation. Note the position of Almen saturation.

5.4.3 6061-T6 Aluminum Alloy

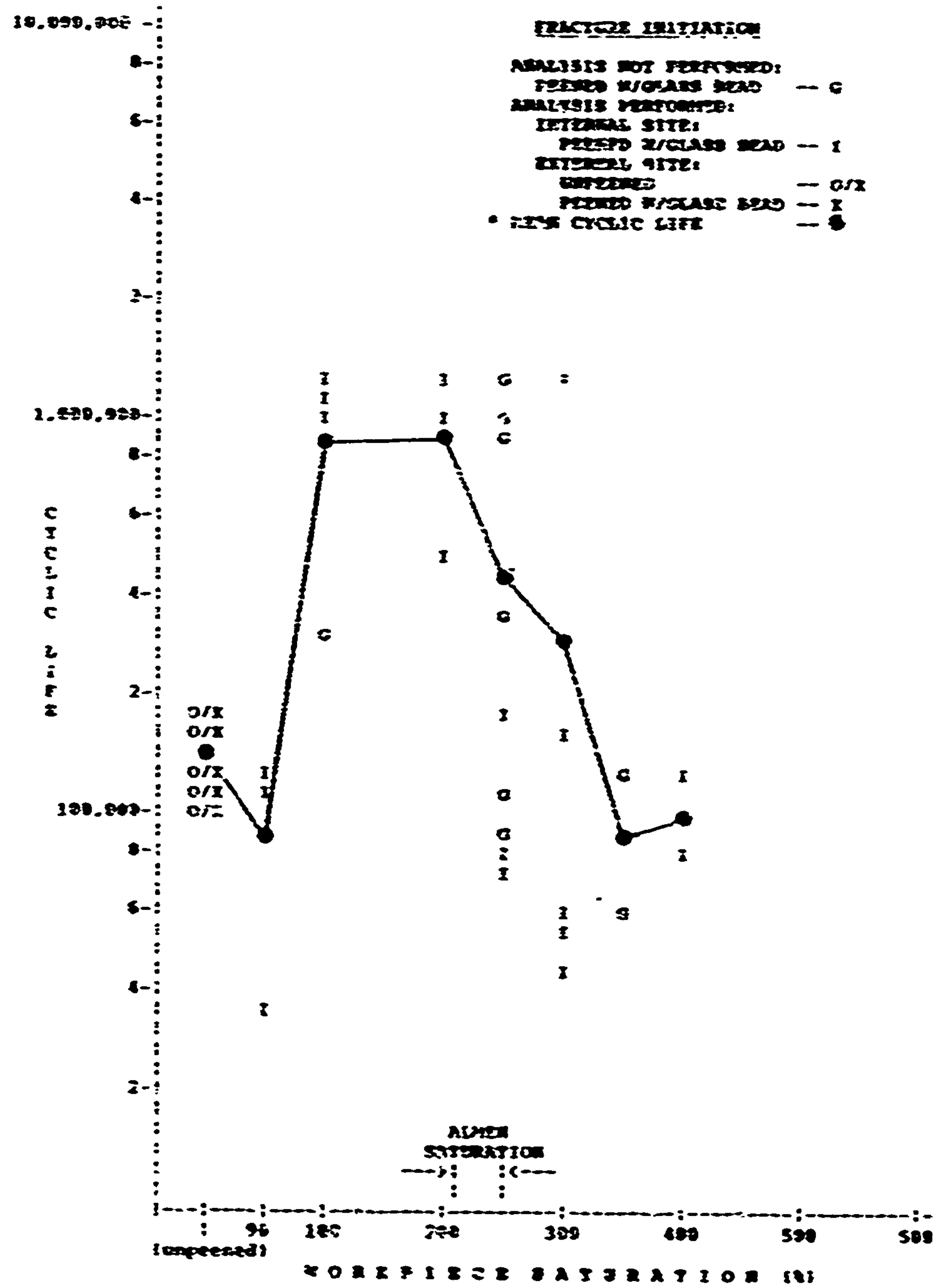
Figure 72 and Table A-19 (Appendix A) present the data for fatigue life versus workpiece saturation on 6061-T6. Specimens were peened incrementally from 80-percent up to and including 350-percent workpiece saturation. The test data were obtained at a maximum stress of 40 ksi.

RESULTS

Mean fatigue life peaked at 100-percent workpiece saturation. Fatigue life generally decreased as workpiece saturation increased above 100-percent.

5.4.4 7075-T6 Aluminum Alloy

Figure 73 and Table A-20 (Appendix A) present the data for fatigue life versus workpiece saturation on 7075-T6 specimens. Specimens were peened in increments of workpiece saturation ranging from 80-percent

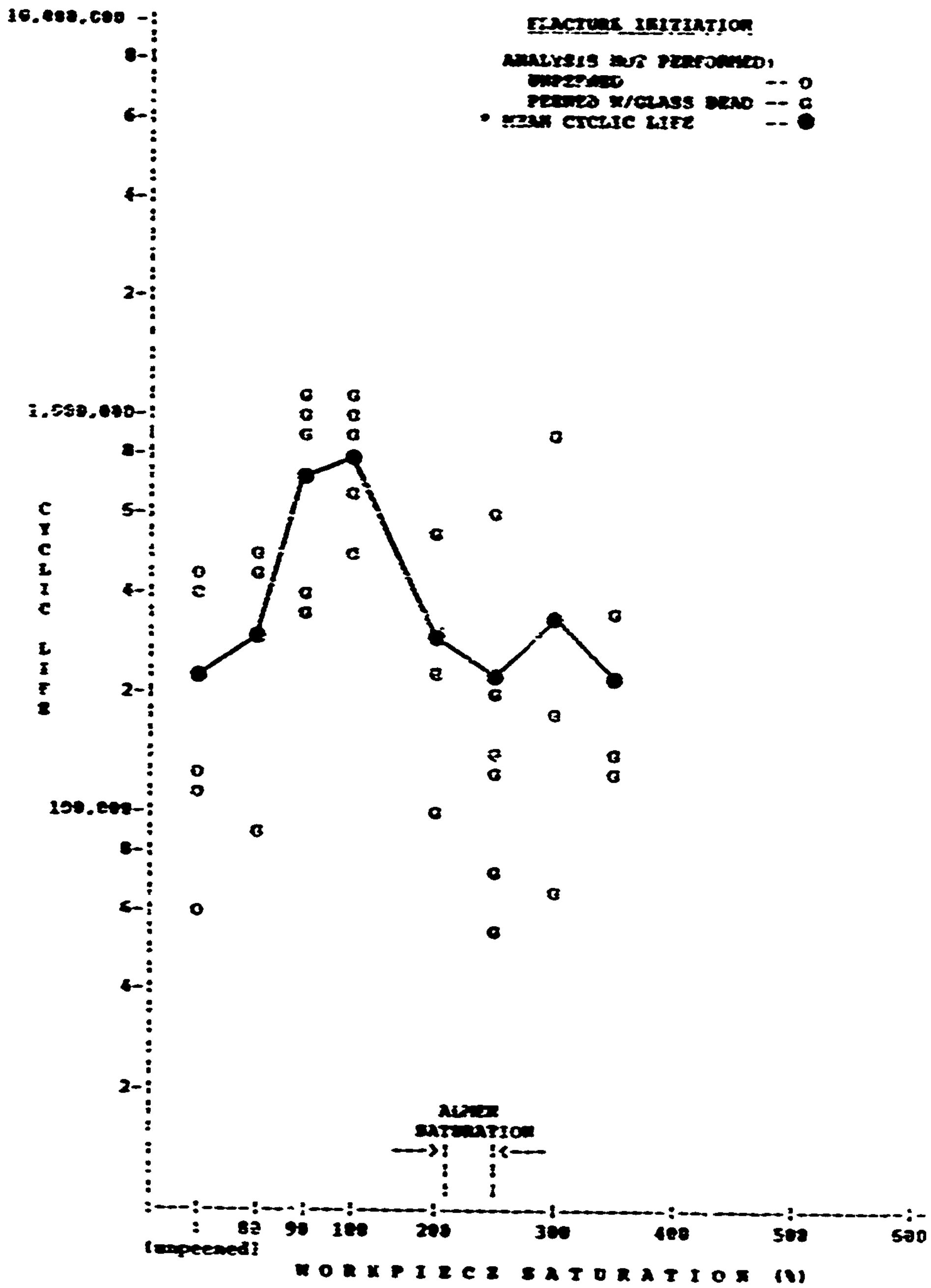


*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

TEST GROUP : FATIGUE LIFE VERSUS WORKPIECE SATURATION (TASK 4)
MATERIAL : 2024-T4 ALUMINUM 100/119 BHN (LOT C-0001)
SPECIMEN SURFACE : LATHE TURNED & POLISHED (C)
ALMEN INTENSITY : 0.001GA (OPTIMUM PER TASK 2)
MEDIA SIZE/TYPE : MIL-13 GLASS BEAD
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 47

FIGURE 71

FATIGUE RESULTS VERSUS WORKPIECE SATURATION, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION OF 2024-T4 ALUMINUM

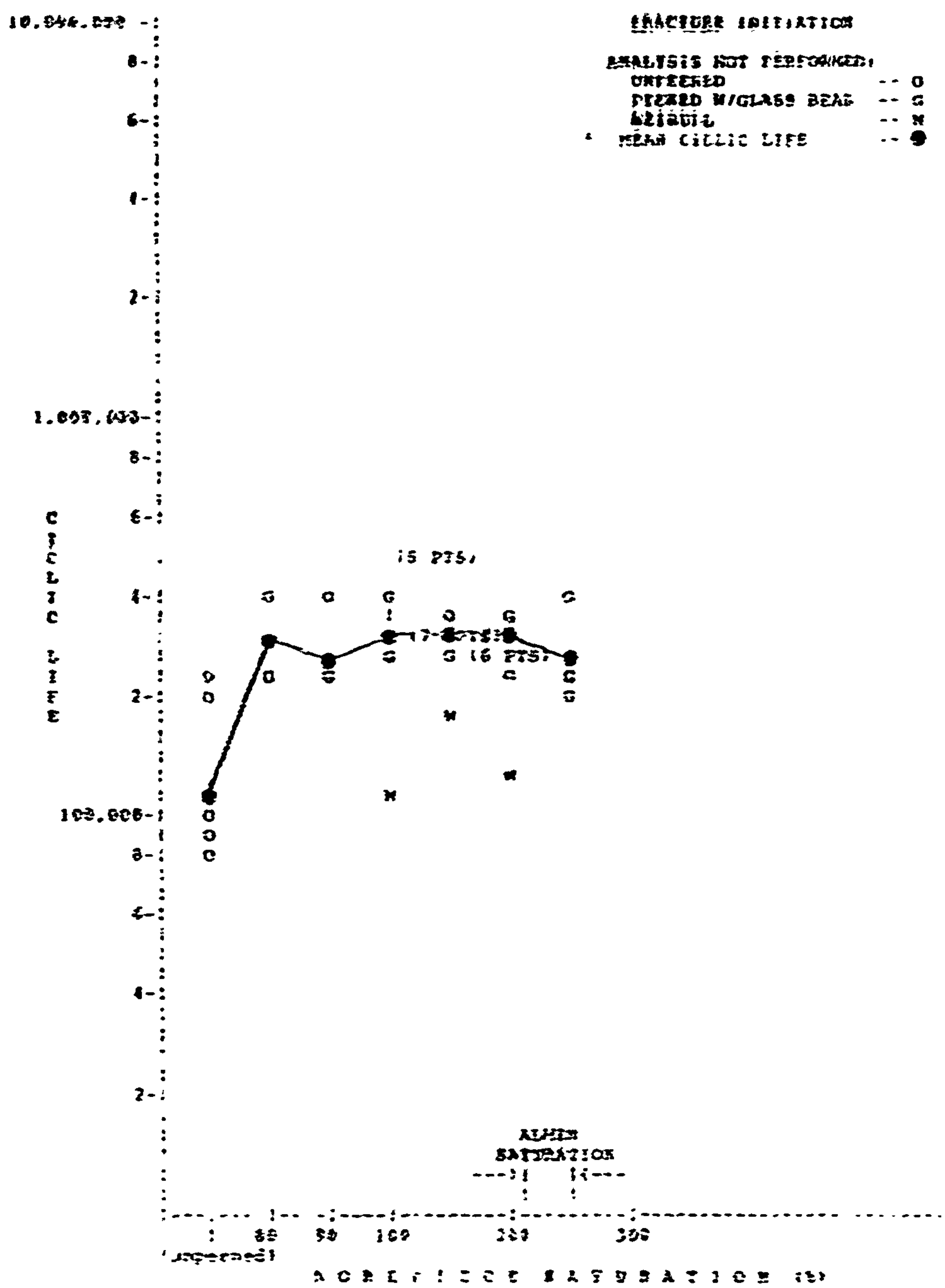


*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT <u>APPENDIX A</u> FOR COMPLETE DATA.

TEST GROUP :	FATIGUE LIFE VERSUS WORKPIECE SATURATION (TASK 4)
MATERIAL :	6061-T6 ALUMINUM 93/100 HBN (LOT C-0003)
SPECIMEN SURFACE :	LATHE TURNED & POLISHED (C)
ALMEN INTENSITY :	0.0010A (OPTIMUM PER TASK 2)
MEDIA SIZE/TYPE :	MIL-13 GLASS BEAD
ANGLE OF IMPACT :	90 DEGREES
MAXIMUM STRESS (KSI) :	40

FIGURE 72

FATIGUE RESULTS VS. WORKPIECE SATURATION, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION OF 6061-T6 ALUMINUM



*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

TEST GROUP : FATIGUE LIFE VERSUS WORKPIECE SATURATION (TASK 4)
MATERIAL : 7075-T6 ALUMINUM 143 BHN (LOT C-0002)
SPECIMEN SURFACE : LATHE TURNED & POLISHED (C)
ALMEN INTENSITY : 0.0010A (OPTIMUM PER TASK 2)
MEDIA SIZE/TYPE : MIL-13 GLASS BEAD
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 56

FIGURE 73

FATIGUE RESULTS VS. WORKPIECE SATURATION, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION OF 7075-T6 ALUMINUM

through 250-percent. The test data were obtained at a maximum stress of 58 ksi.

RESULTS

Weibull fatigue life was highest at 150-percent workpiece saturation (75-percent Almen saturation). This is consistent with the findings in Phase I. Fatigue life at saturation levels above 150-percent workpiece saturation showed a consistent trend toward increasing scatter and lower fatigue life at the bottom of the scatter range.

5.4.5 7075-T73 Aluminum Alloy

Figure 74 and Table A-21 (Appendix A) present the fatigue life versus workpiece saturation data for 7075-T73. Specimens were peened in increments of workpiece saturation ranging from 100-percent through 800-percent. The test data were obtained at a maximum stress condition of 50 ksi.

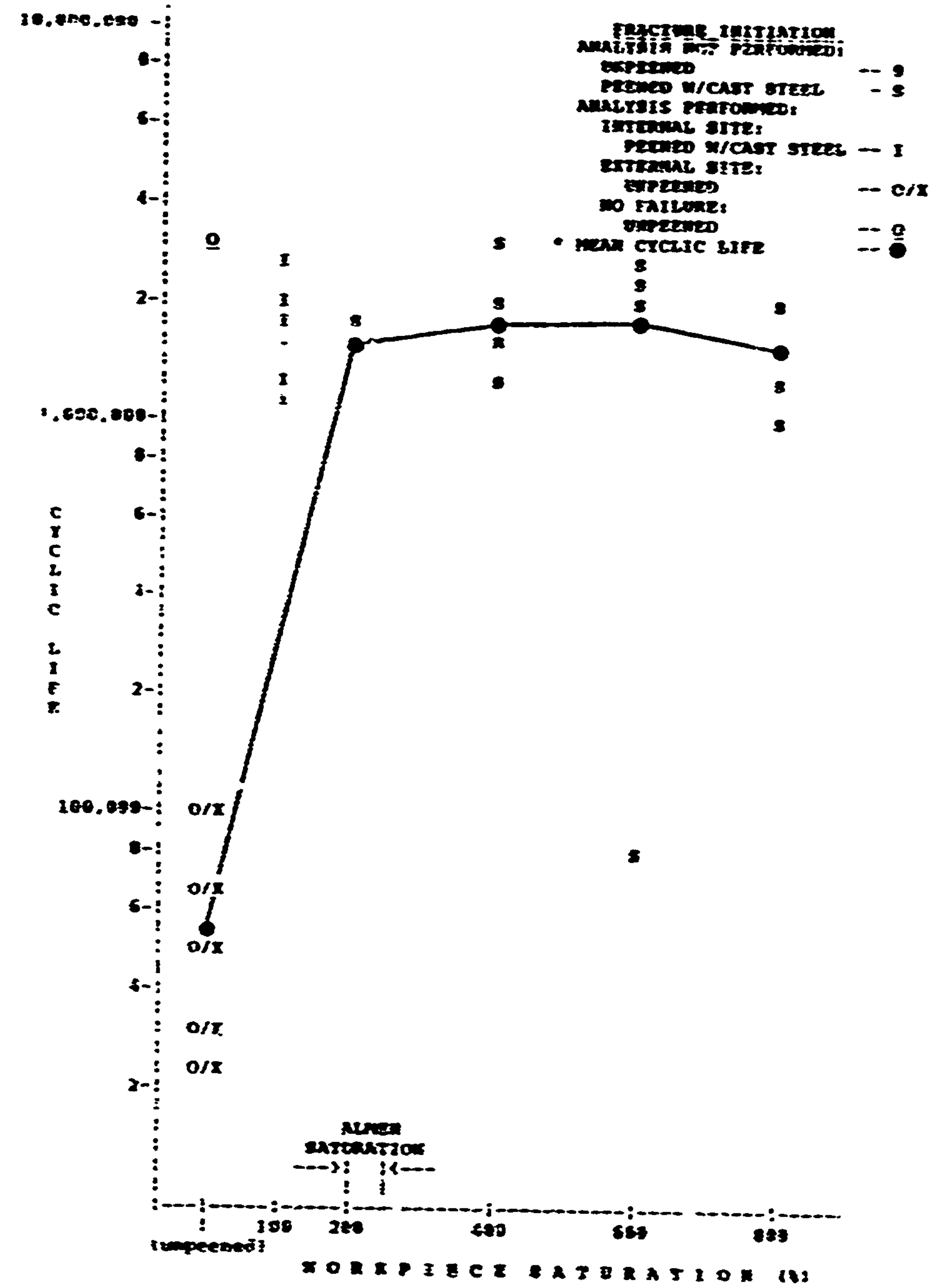
RESULTS

This material exhibits relative insensitivity to varying workpiece saturation levels.

Figure 75 shows specimen number 2465's peened surface at 200X magnification at optimum intensity of 0.0030A at 100-percent workpiece saturation.

Figure 76 shows specimen 2498 peened surface at 200X magnification at optimum intensity of 0.0020A at 800-percent workpiece saturation.

The peened surface comparison of the two photo micrographs at high magnification reveal extensive small fissures surrounding shot impact craters on the surface of the 800-percent workpiece saturation specimen. There is quite clearly a difference in these groups of small fissures from the large surface folds that constitute PSKF. The surface of the 100-percent workpiece saturation specimen does not exhibit these small fissures. This is consistent with Phase I findings.



*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT <u>APPENDIX A</u> FOR COMPLETE DATA.

TEST GROUP :	FATIGUE LIFE VERSUS WORKPIECE SATURATION (TASK 4)
MATERIAL :	7075-T73 ALUMINUM 158 HBN (LOT C-0017)
SPECIMEN SURFACE :	LATHE TURNED & POLISHED (C)
ALMEN INTENSITY :	0.0030A
MEDIA SIZE, TYPE :	MIL-11 GLASS BEAD
ANGLE OF IMPACT :	90 DEGREES
MAXIMUM STRESS (KSI) :	50

FIGURE 7A

FATIGUE RESULTS VS. WORKPIECE SATURATION, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION OF 7075-T73 ALUMINUM

FIGURE 75- 7075-T73 ALUM AT 0.0020A AT 100% AT 200X, IMPINGEMENTS OVERLAP COMPLETELY

FIGURE 76- 7075-T73 ALUM AT 0.0020A AT 800% AT 200X, IMPINGEMENT PERIPHERY BEATEN DOWN

5.4.6 4340 Alloy Steel - Airmelt - 40/42 HRC

Figure 77 and Table A-22 (Appendix A) present the data for fatigue life versus workpiece saturation which were obtained at a maximum stress condition of 165 ksi.

Specimens were peened in increments of workpiece saturation ranging from 100-percent through 400-percent.

RESULTS

The data indicated that increasing percentages of workpiece saturation did not adversely affect fatigue life up to and including 350-percent workpiece saturation. At 400-percent workpiece saturation fatigue life was significantly lower than all other levels.

5.4.7 4340 Alloy Steel - Airmelt - 48/50 HRC

Figure 78 and Table A-23 (Appendix A) present the data for fatigue life versus workpiece saturation. Specimens were peened in increments of workpiece saturation ranging from 100-percent through 400-percent. Test data were obtained at a maximum stress condition of 170 ksi.

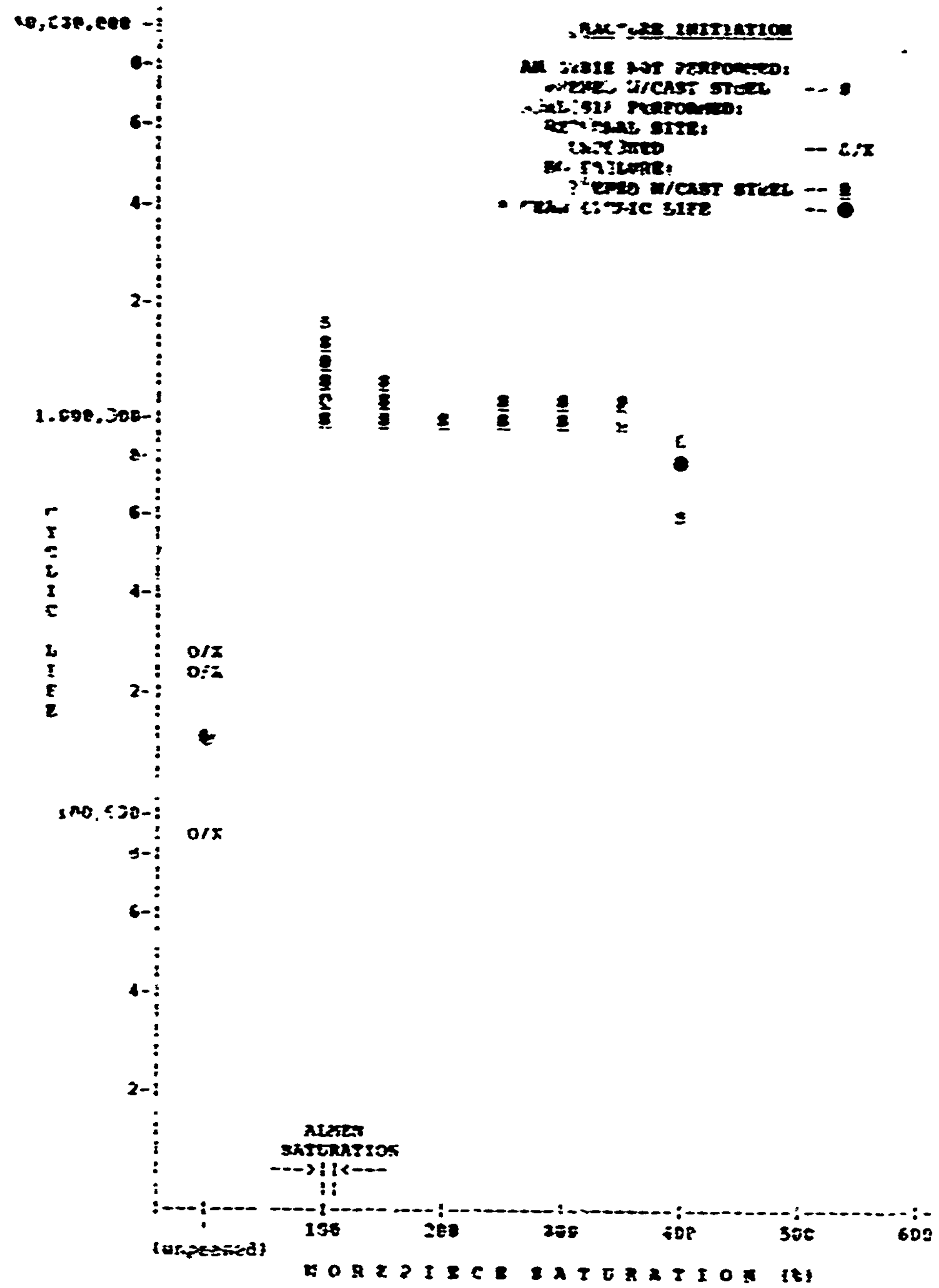
RESULTS

The low end of the scatter range is approximately the same for all workpiece saturation conditions. No apparent trend can be ascertained other than a reduction in mean fatigue life as saturation level increased.

Fracture surface evaluations revealed non metallic inclusions at all fracture initiation sites examined.

5.4.8 4340 Alloy Steel - Vacuum Arc Remelt - 48/50 HRC

Figure 79 and Table A-24 (Appendix A) present the data for fatigue life versus workpiece saturation. Specimens were peened in increments of workpiece saturation from 100-percent through 600-percent. Test data were obtained at a maximum stress condition of 195 ksi.

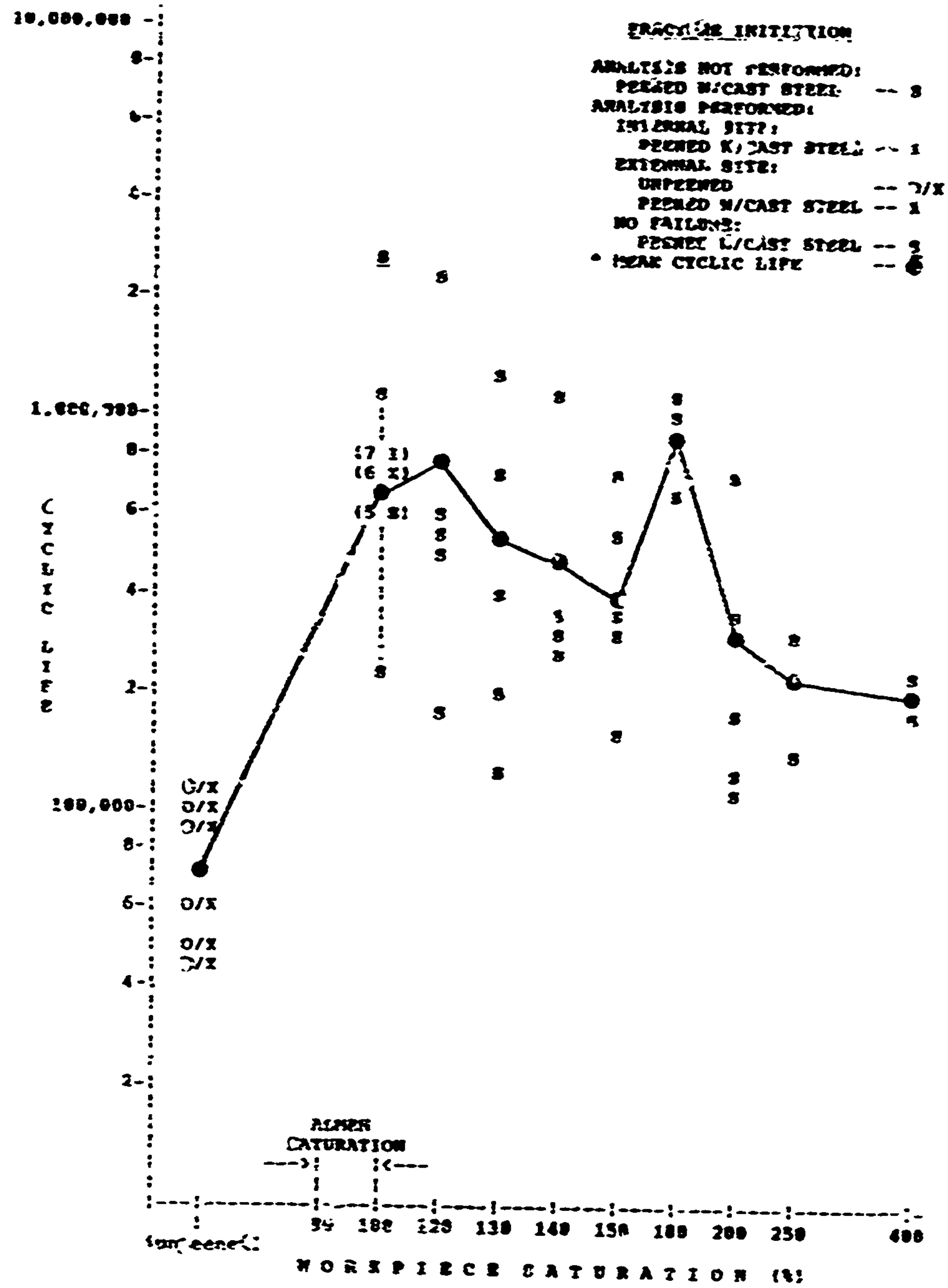


*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

TEST GROUP :	FATIGUE LIFE VERSUS WORKPIECE SATURATION (TASK 3)
MATERIAL :	4340 AIRMELT STEEL 40/42 HRC (LOT C-0020)
SPECIMEN SURFACE :	GROUND & POLISHED (L)
ALMEN INTENSITY :	0.0040A (OPTIMUM PER TASK 2)
MEDIA SIZE/TYPE :	S-70 CAST STEEL
ANGLE OF IMPACT :	90 DEGREES
MAXIMUM STRESS (KSI) :	155

FIGURE 77

FATIGUE RESULTS VERSUS WORKPIECE SATURATION, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION OF 4340 AIRMELT STEEL 40/42 HRC

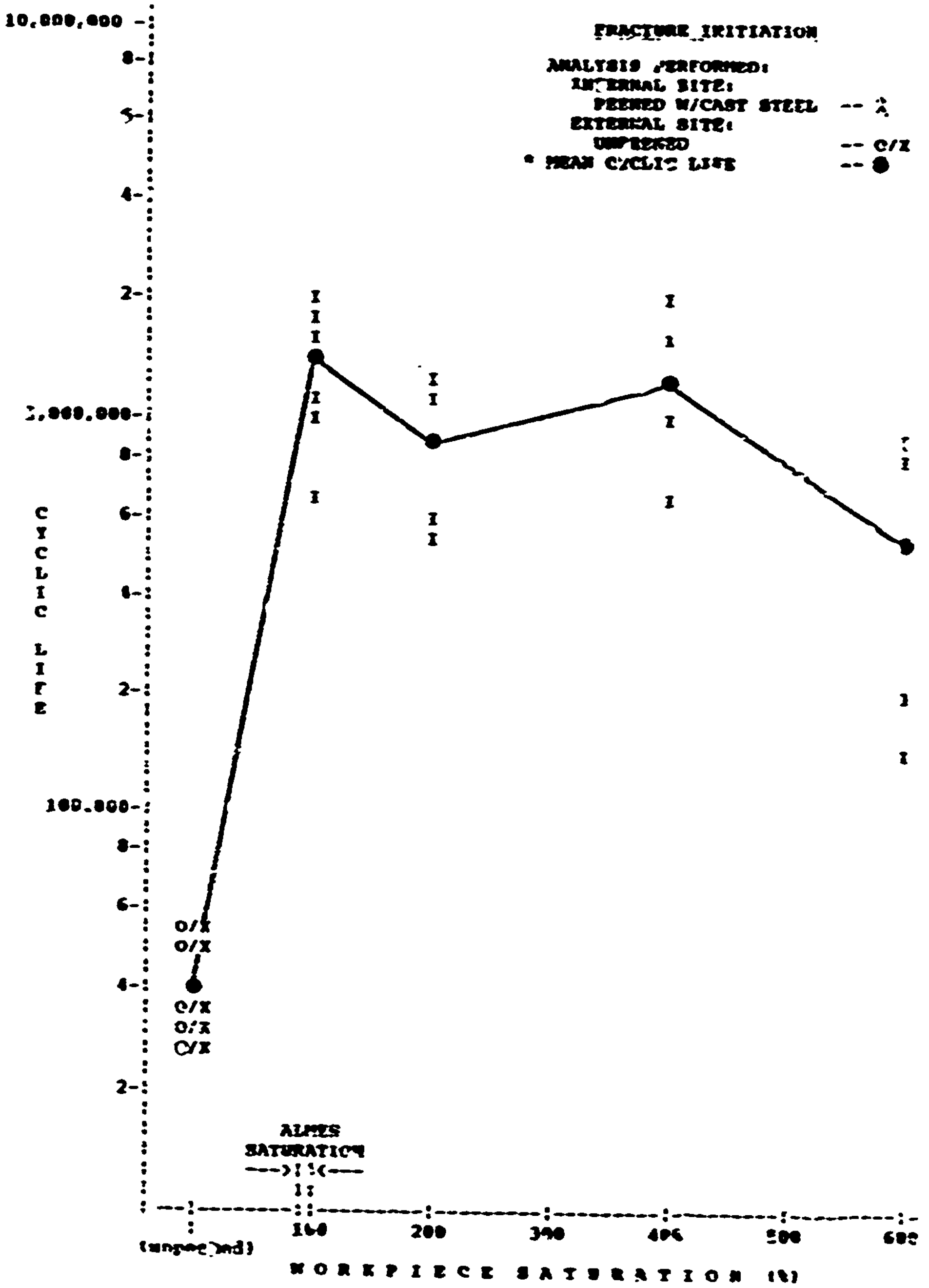


*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

TEST GROUP :	FATIGUE LIFE VERSUS WORKPIECE SATURATION (TASK 4)
MATERIAL :	4340 AIRMELT STEEL 48/50 HRC (LOT C-0021)
SPECIMEN SURFACE :	GROUND AND POLISHED (L)
ALMEN INTENSITY :	0.0080A
MEDIA SIZE/TYPE :	S-70 CAST STEEL
ANGLE OF IMPACT :	90 DEGREES
MAXIMUM STRESS (KSI) :	170

FIGURE 78

FATIGUE RESULTS VS. WORKPIECE SATURATION, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION OF 4340 AIRMELT STEEL 48/50 HRC



*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

TEST GROUP :	FATIGUE LIFE VERSUS WORKPIECE SATURATION (TASK 4)
MATERIAL :	4340 VACUUM ARC REMELT STEEL 48/50 HRC (LOT C-0028
SPECIMEN SURFACE :	GROUND
ALMEN INTENSITY :	0.0020A (OPTIMUM PER TASK 2)
MEDIA SIZE/TYPE :	S-70 CAST STEEL
ANGLE OF IMPACT :	90 DEGREES
MAXIMUM STRESS (KSI) :	195

FIGURE 79

FATIGUE RESULTS VS. WORKPIECE SATURATION, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION OF 4340 VACUUM ARC REMELT 48/50 HRC

RESULTS

A general pattern of decreasing fatigue life as saturation increased is present. However, 100-percent, 200-percent, and 300-percent fatigue life values are very similar. There is a large difference between the fatigue life results obtained in the 600-percent condition as opposed to the 100-percent, 200-percent, and 300-percent conditions, mean fatigue life being far lower in the 600-percent condition. All fracture initiation sites were internal in origin.

Figures 80, 81, and 81A illustrate the differences in surface appearance between specimens peened at 100-percent versus 600-percent workpiece saturation.

5.5 TASK 5 -- THE EFFECT OF PEENING IMPACT ANGLE ON FATIGUE LIFE

This task was aimed at quantifying the effect of peening impact angle on fatigue life. Two materials were employed in the study, 7075-T73 Aluminum and 4340 Steel, VAR, 48/50 HRC. Exclusive of impact angle and shot velocity (which was increased as impact angle was lowered to hold intensity constant), all peening parameters were the same as used in determining optimum intensity in Task 2. This included use of optimum intensity as defined in Task 2. Impact angle conditions selected were 45, 60, and 90 degrees.

5.5.1 7075-T73 Aluminum

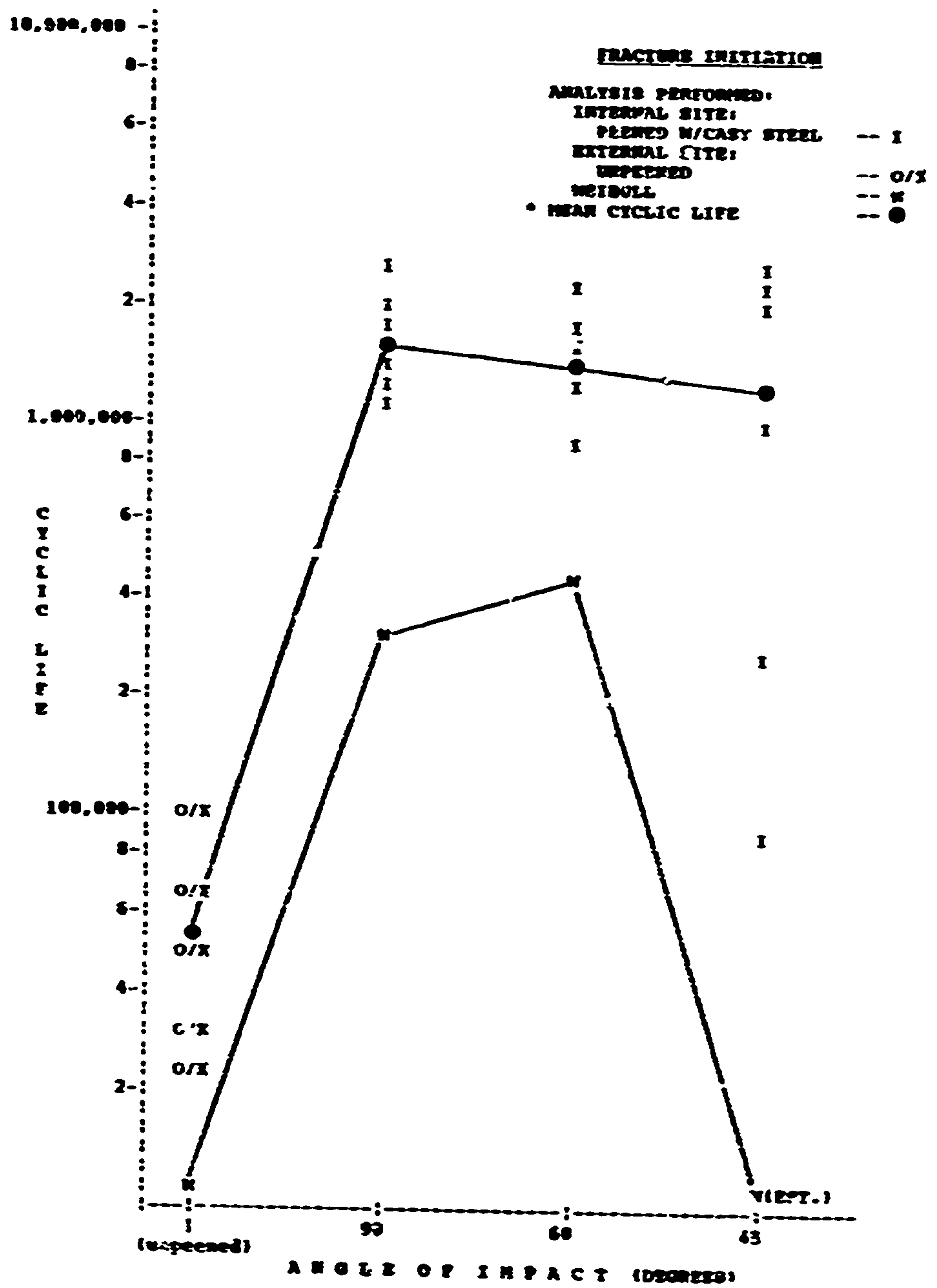
Test data were obtained at a maximum stress condition of 50 ksi. The intensity level used was 0.0020A at 100-percent workpiece saturation per Task 4.

Figure 82 and Table A-25 (Appendix A) present the fatigue life versus angle of impact data.

FIGURE 80- 4340 STEEL VAR 48/50 HRC AT 0.0020A AT 200X, 100% WORKPIECE SATURATION, TOOL MARKS VISIBLE

FIGURE 81- 4340 STEEL VAR 48/50 HRC AT 0.0020A AT 200X, 600% WORKPIECE SATURATION, TOOL MARKS NEARLY OBLITERATED

FIGURE 81A- FIGURE 81 AT 1000X



*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

TEST GROUP :	FATIGUE LIFE VERSUS ANGLE OF IMPACT (TASK 5)
MATERIAL :	7075-T73 ALUMINUM 136 BHN (LOT C-6030)
SPECIMEN SURFACE :	LATHE TURNED AND POLISHED (C)
ALMEN INTENSITY :	0.0020A (OPTIMUM PER TASK 2)
WORKPIECE SATURATION :	100% (OPTIMUM PER TASK 4)
MEDIA SIZE/TYPE :	S-70 CAST STEEL
MAXIMUM STRESS (KSI) :	50

FIGURE 82

FATIGUE RESULTS VERSUS IMPACT ANGLE, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 7075-T73 ALUMINUM

RESULTS

Mean fatigue life decreased and Weibull fatigue life increased marginally as impact angle was decreased from 90 to 60 degrees. The size of the scatter band for the 60-degree data approximated that of the 90-degree data. As angle of impact was decreased to 45 degrees, Weibull fatigue life decreased to below that of the unpeened control specimens. The data scatter band increased twofold from the 60-degree or 90-degree impact angle conditions to the 45-degree impact angle conditions.

Since the primary crack nucleation sites were internal for all specimens, PSEF size and depth were not causal to primary failure. However, PSEF were larger in the 60-degree degree versus the 90-degree impact angle condition (Figures 118 and 119). We believed that the surfaces with larger PSEF were inherently weaker, and as such, were associated with earlier crack breakthrough to the surface and subsequent total specimen failure. (Figures are in 6.0 Discussion section.)

5.5.2 4340 Alloy Steel - Vacuum Arc Remelt - 48/50 HRC

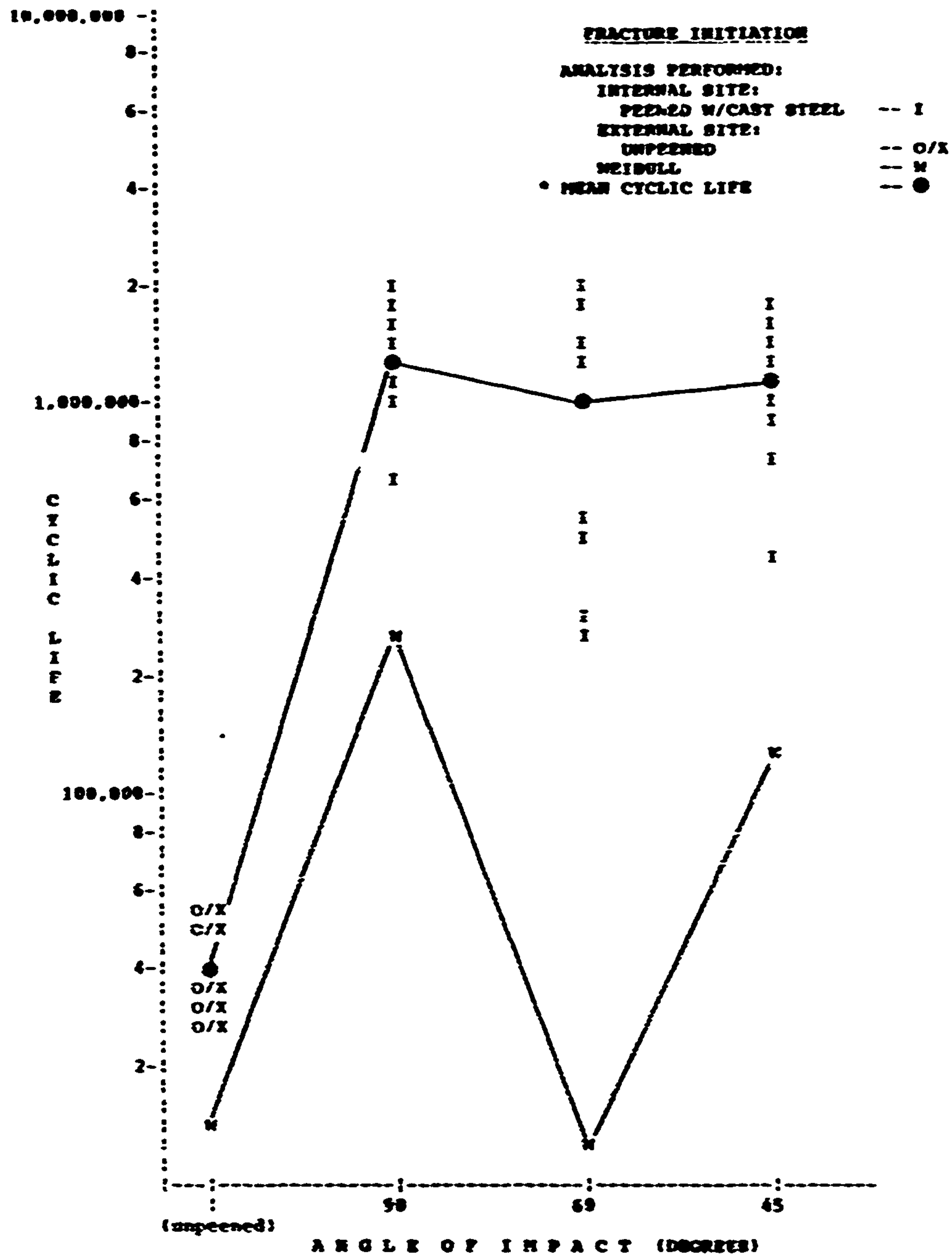
Peening was at 0.0020A and optimum saturation level per Task 4 (100-percent workpiece saturation) at 45, 60, and 90 degrees.

The test data were obtained at a maximum stress of 195 ksi.

Figure 83 and Table A-26 (Appendix A) present the data for fatigue life versus peening angle of impact for 4340 Alloy Steel - Vacuum Arc Remelt.

RESULTS

The 90-degree impact angle data has significantly higher Weibull and mean fatigue life than either 60-degree or 45-degree impact angle. The 60-degree impact angle data had a lower Weibull fatigue



*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

TEST GROUP :	FATIGUE LIFE VERSUS ANGLE OF IMPACT (TASK 6)
MATERIAL :	4340 VACUUM ARC REMELT STEEL 48/50 HRC (LOT C-0028, C-0031)
SPECIMEN SURFACE :	GROUND
ALMEN INTENSITY :	0.0020A (OPTIMUM PER TASK 2)
WORKPIECE SATURATION :	100% (OPTIMUM PER TASK 4)
MEDIA SIZE/TYPE :	S-70 CAST STEEL
MAXIMUM STRESS (KSI) :	195

FIGURE 83

FATIGUE RESULTS VS. IMPACT ANGLE, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 4340 VACUUM ARC REMELT STEEL 48/50 HRC

life and approximately the same mean fatigue life as the 45-degree data.

Primary crack nucleation sites were internal on all specimens.

Figure 84 shows specimen 2349 peened surface with 90-degree impact angle and 0.0020A peening intensity, at 200X magnification.

Figure 85 shows specimen 2626 peened surface at 60-degree angle, 200X magnification and 0.0020A optimum peening intensity. Notice the greater degree and the directional flow of surface plastic deformation as compared to the 90- degree impact angle condition in Figure 84.

Figure 86 shows specimen 2353 peened surface at 45-degree angle, 200X magnification and 0.0020A optimum peening intensity. The surface exhibits a greater degree of plastic deformation and discontinuities associated with PSEF than are present in 90-and 60-degree impact angle specimens. (See Figures 120 and 121 for cross sections at 90-degree and 60-degree angle in 6.0 Discussion section.)

5.6 TASK 6 -- EFFECT OF SHOT BROKEN PARTICLE CONTENT ON FATIGUE LIFE

The purpose of this task was to quantify the relationship between shot broken particle content and specimen fatigue life. Two materials were employed: 7075-T73 Aluminum and 4340 Steel, VAR, 48/50 HRC.

Test specimens of each material were peened at optimum intensity from Task 2 utilizing MIL-S-13165-B Table I cast steel shot having increasing percentages of L.G. 80 cast steel grit per MIL-S-851C added to simulate broken media content of 25-percent, 50-percent and 75-percent by weight. (Note that cast steel grit is manufactured by fracturing cast steel shot.)

FIGURE 84- 4340 STEEL VAR 48/50 HRC AT 0.0020A AT 200X, 90 DEG. ANGLE OF IMPACT, RADIAL PLASTIC DEFORMATION

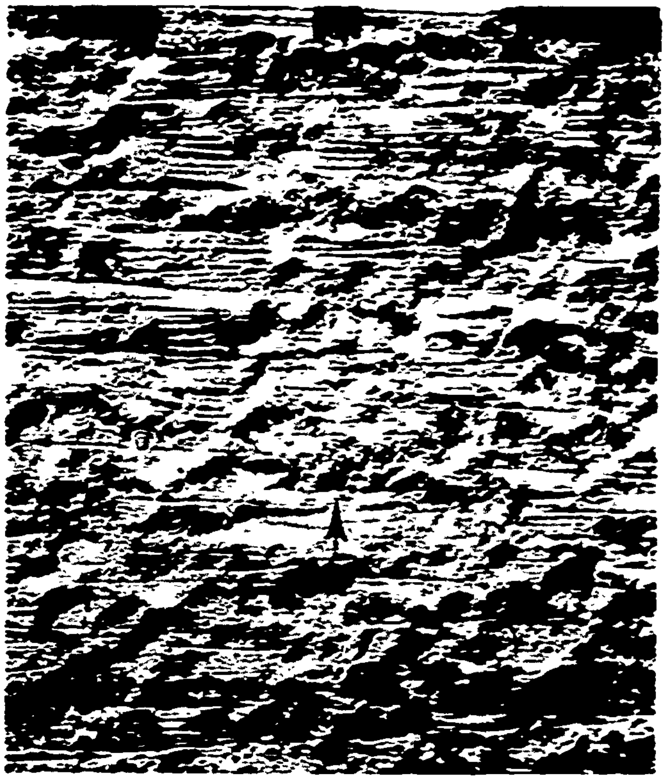


FIGURE 85- 4340 STEEL VAR 48/50 HRC AT 0.0020A AT 200X, 60 DEG. ANGLE OF IMPACT, DIRECTIONAL DEFORMATION, DIRECTION OF PLASTIC FLOW →

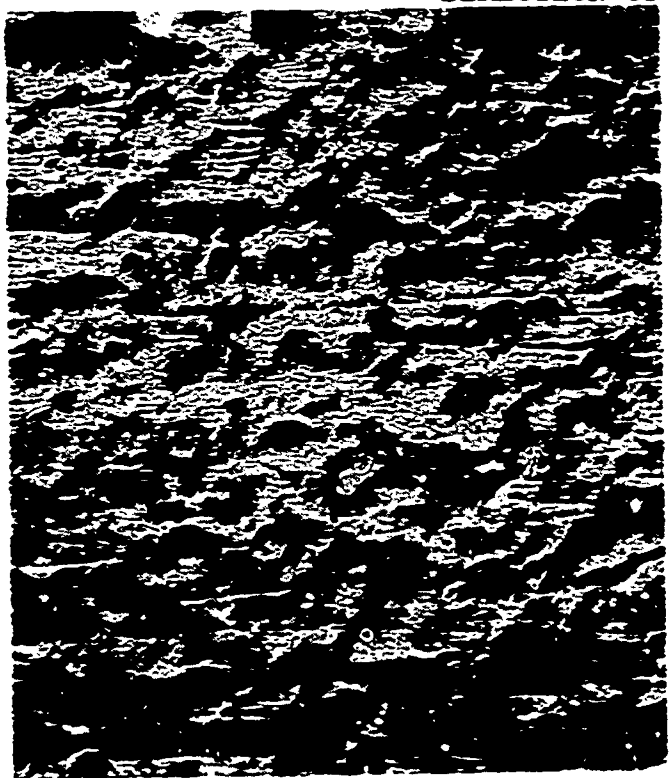


FIGURE 86- 4340 STEEL VAR 48/50 HRC AT 0.0020A AT 200X, 45 DEG. ANGLE OF IMPACT, DIRECTIONAL DEFORMATION, DIRECTION OF PLASTIC FLOW →

5.6.1 7075-T73 Aluminum Alloy

Figure 87 and Table A-27 (Appendix A) present the data for fatigue life versus broken particle content of the shot. The test data were obtained at a maximum stress of 50 ksi.

RESULTS

Mean and Weibull fatigue life were highest at the 2-percent or less broken particle content levels. Increasing broken particle content was associated with decreasing Weibull and mean fatigue life. The one unusually low specimen fatigue life value at the 50-percent broken particle content level significantly reduced the Weibull fatigue life for this condition.

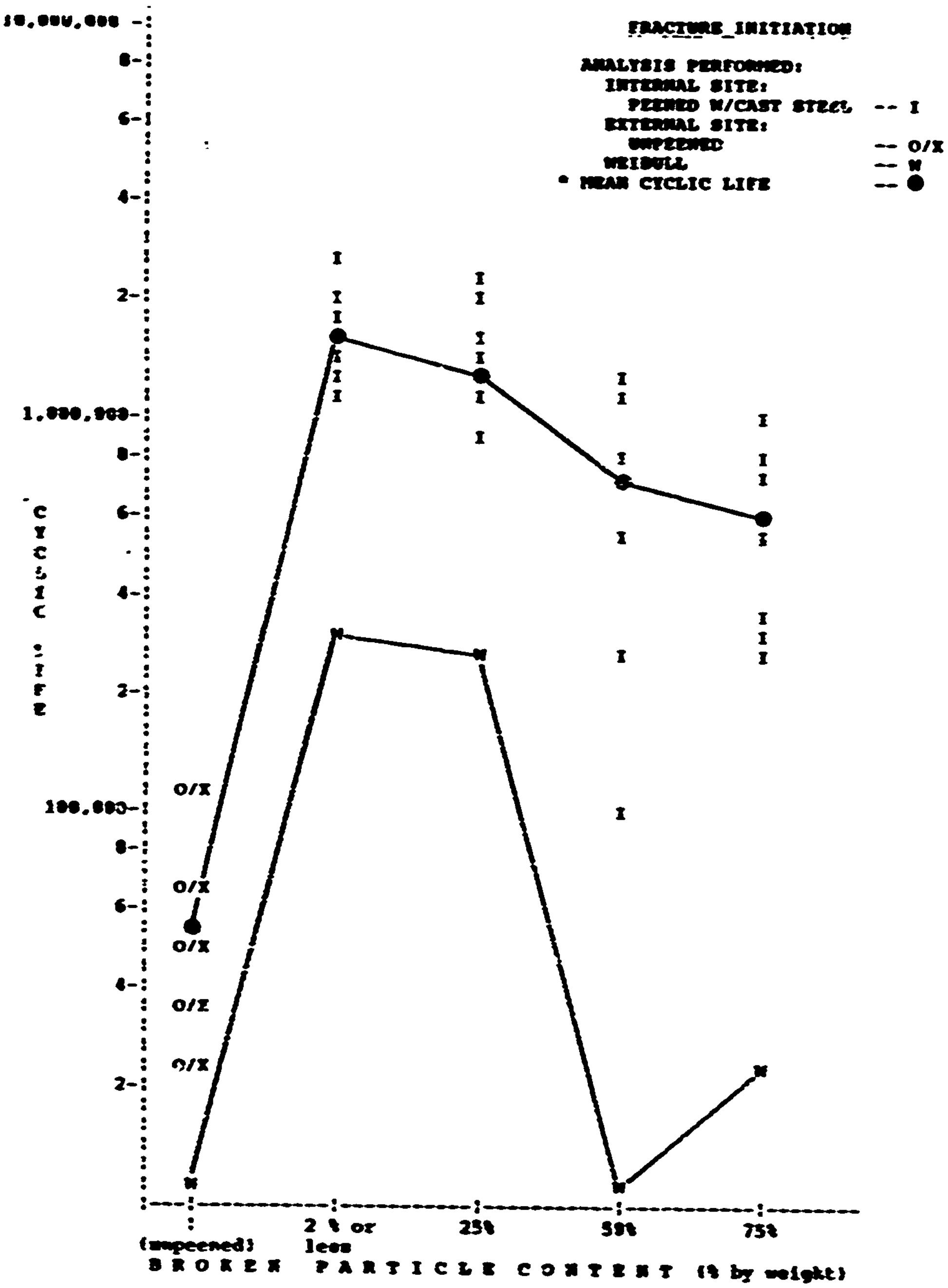
Figures 88, 89, and 90 illustrate the increasing number of angular impingements associated with increasing shot broken particle content. Figures 91, 92, 93, and 94 show these surfaces in cross section.

5.6.2 4340 Alloy Steel - Vacuum Arc Remelt - 48/50 HRC

Figure 95 and Table A-28 (Appendix A) present the data for fatigue life versus shot broken particle content on 4340 VAR 48/50 HRC. The test data were obtained at a maximum stress of 195 ksi.

RESULTS

Increasing broken particle content was closely associated with decreasing specimen fatigue life. Mean and Weibull fatigue life decreased linearily as broken shot content increased. At the 25-percent and 50-percent broken particle conditions, fracture initiation sites were all internal. In the 75-percent broken particle condition specimens exhibited primary and secondary crack nucleation sites of both internal and external origin.



*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

TEST GROUP : FATIGUE LIFE VS. BROKEN PARTICLE CONTENT (TASK 6)
MATERIAL : 7075-T73 ALUMINUM 136 HBN (LOT C-0030)
SPECIMEN SURFACE : LATHE TURNED AND POLISHED (C)
ALMEN INTENSITY : 0.0020A (OPTIMUM PER GROUP B)
WORKPIECE SATURATION : 100% (OPTIMUM PER GROUP G)
MEDIA(SHOT/GRIT) SIZE/TYPE: S70 CAST STEEL/LG-80 CAST STEEL
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 50

FIGURE 87

FATIGUE RESULTS VS. BROKEN PARTICLE CONTENT, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION OF 7075-T73 ALUMINUM

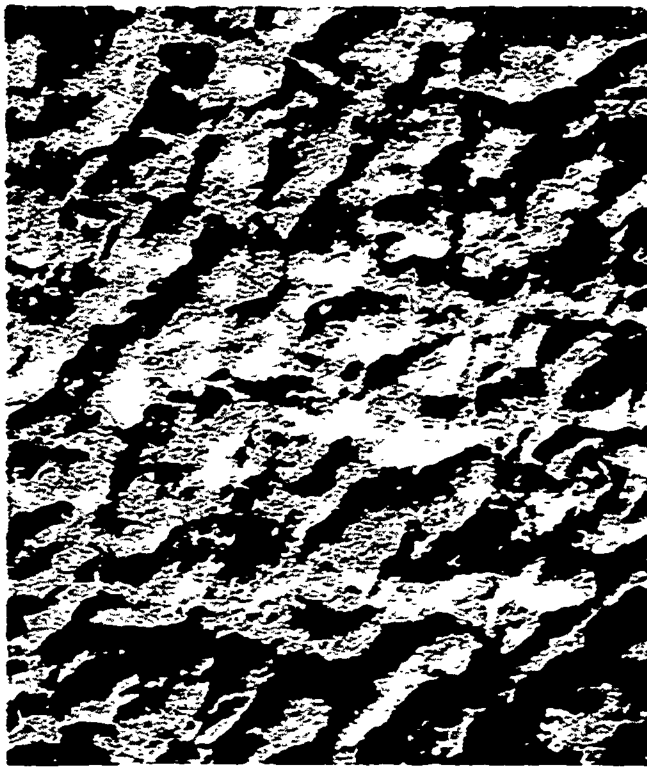


FIGURE 88- 7075-T73 ALUM AT 0.0020A
LESS THAN 2% BROKEN PARTICLE CONTENT
200X

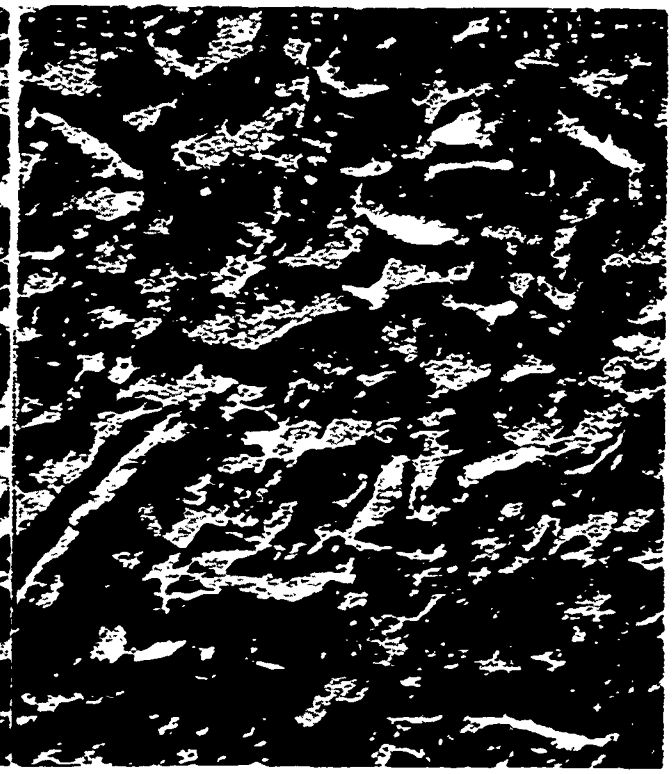


FIGURE 89- 7075-T73 ALUM AT
0.0020A, 25% BROKEN PARTICLE
CONTENT, ACCICULAR IMPINGEMENT,
200X

FIGURE 90- 7075-T73 ALUM AT 0.0020A AT 200X
75% BROKEN PARTICLE CONTENT
SEVERE ACCICULAR IMPINGEMENTS

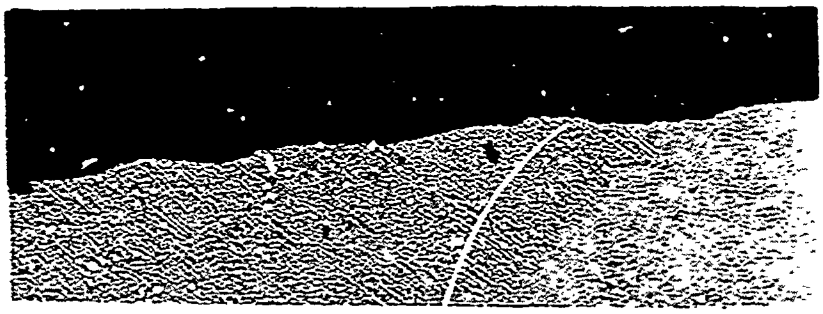


FIGURE 91 - 7075-T73 AT 0.0020A AT 700X, WITH LESS THAN 2% BROKEN PARTICLE CONTENT IN MEDIA, CONTIGUOUS SURFACE

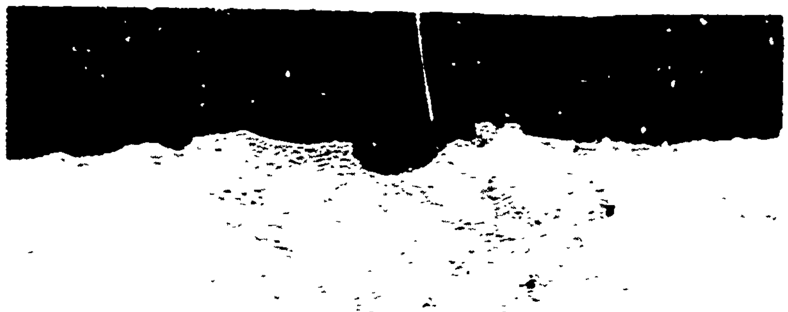


FIGURE 92- 7075-T73 AT 0.0020A AT 700X, WITH 25% BROKEN PARTICLE CONTENT IN MEDIA, NOTICE ACCICULAR IMPINGEMENTS

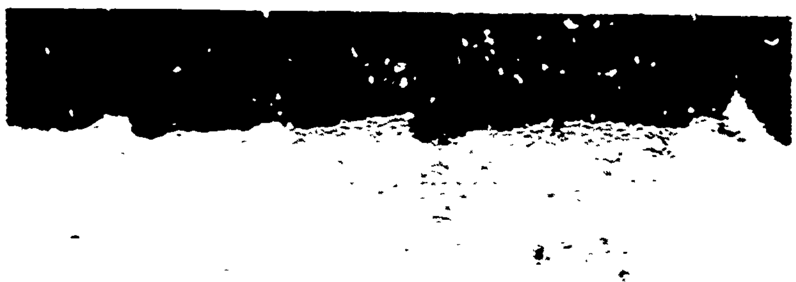


FIGURE 93- 7075-T73 AT 0.0020A AT 700X, WITH 50% BROKEN PARTICLE CONTENT IN MEDIA, SURFACE EROSION HAS BEGUN

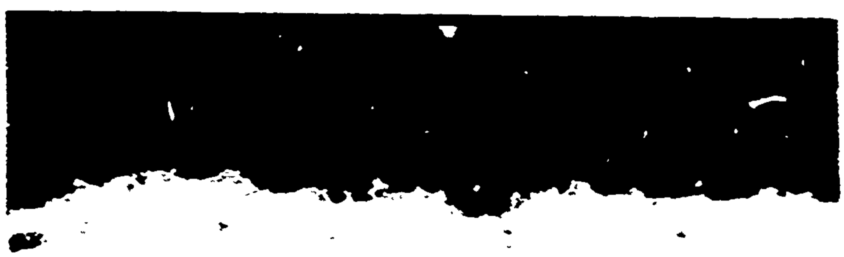
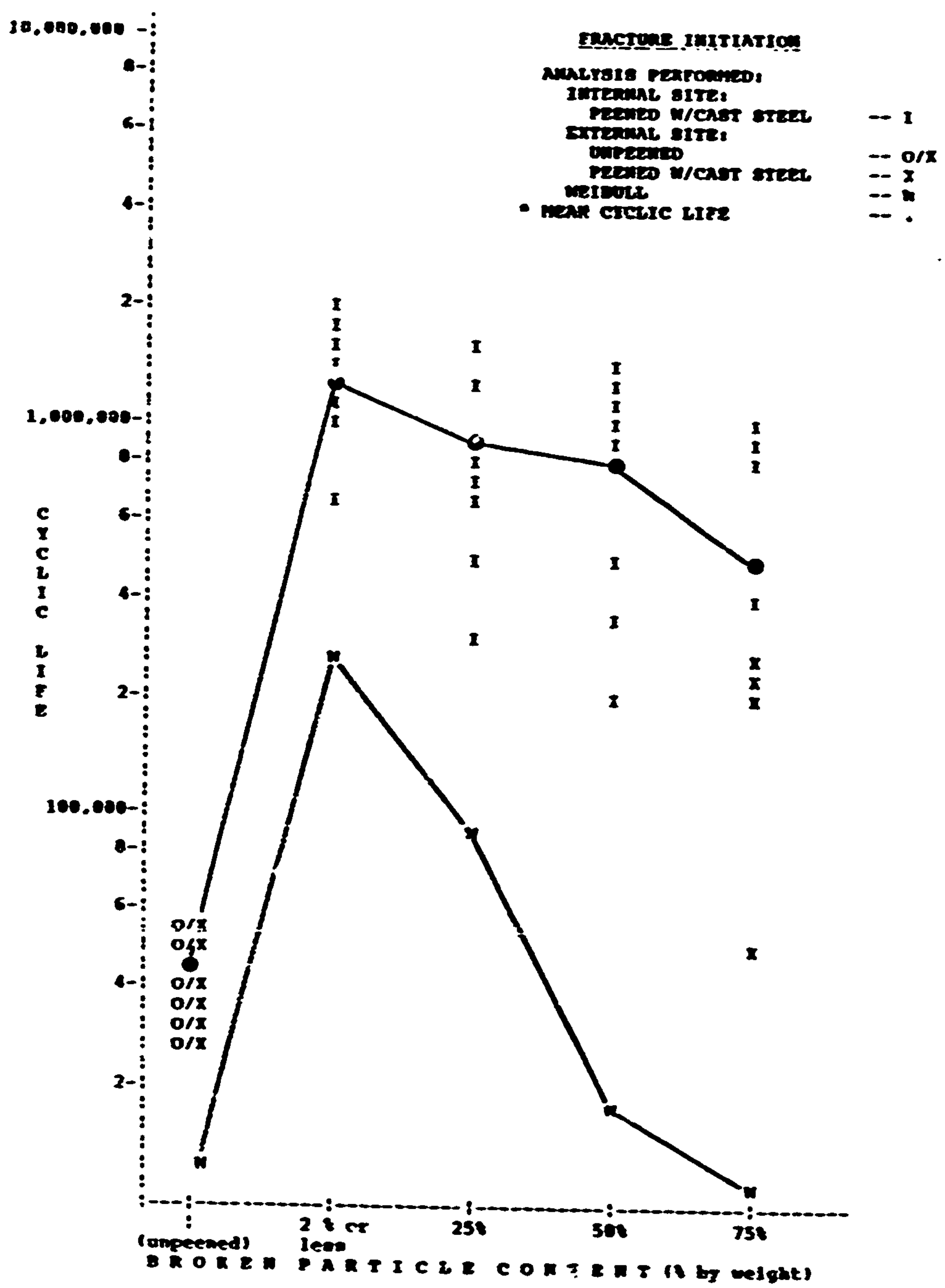


FIGURE 94 - 7075-T73 AT 0.0020A AT 700X, WITH 75% BROKEN PARTICLE CONTENT IN MEDIA, SEVERE SURFACE EROSION



*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

TEST GROUP :	FATIGUE LIFE VS. BROKEN PARTICLE CONTENT (TASK C)
MATERIAL :	4340 VACUUM ARC REMELT STEEL 48/50 HRC (LOT C-003
SPECIMEN SURFACE :	GROUND
ALMEN INTENSITY :	0.0020A (OPTIMUM PER TASK 2)
WORKPIECE SATURATION :	100% (OPTIMUM PER TASK 4)
MEDIA (SHOT/GRIT) SIZE/TYPE :	S-70 CAST STEEL/ LG-80 CAST STEEL
ANGLE OF IMPACT :	90 DEGREES
MAXIMUM STRESS (KSI) :	195

FIGURE 95

FATIGUE RESULTS VS. BROKEN PARTICLE CONTENT, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION OF 4340 VACUUM ARC REMELT STEEL 48/50 HRC

Figures 96, 97, and 98 illustrate the increasing number of angular impingements associated with increasing shot broken particle content. Figures 99,100,101, and 102 show these surfaces in cross section.

5.7 TASK 7 -- EFFECT OF PEENING SHOT TYPE ON FATIGUE LIFE

The purpose of this task was to determine if the type of peening shot affects workpiece fatigue life, or if the general trends in fatigue life versus intensity data would be affected by media size/type. 7075-T73 specimens were peened to various Almen intensities using either glass beads per MIL-G-9954A or cast steel shot per MIL-S-13165B, Table 1.

Test data were obtained at a maximum stress condition of 50 ksi. Figure 103 and Table A-29 (Appendix A) present the data.

RESULTS

Unpeened control specimens had a mean fatigue life of 458,000 cycles. At 0.0010A and 0.0030A intensities, both the mean life and the scatter band of data are similar (Figure 103). No significant differences in fatigue life at a given intensity, or in the trend of fatigue life as intensity increased, was apparent for steel and glass shot.

It is apparent from examination of the results that the two peening medias produced essentially identical fatigue life results.

5.8 TASK 8 -- ESTABLISHING WHETHER INCREASED SHOT SIZE OR A SECONDARY LOW INTENSITY PEENING AFFECTS SPECIMEN SURFACE INTEGRITY AS IT RELATES TO PSEF SIZE AND DEPTH AT A GIVEN INTENSITY.

Testing was accomplished by comparing the size and depth of PSEF in the following conditions:

(1) 7075-T73 0.0100A, 0.011 dia. shot
(2) 7075-T6 0.0110A, 0.023 dia. shot

FIGURE 96- 4340 STEEL VAR 48/50 HRC AT 0.0020A, LESS THAN 2% BROKEN PARTICLE CONTENT, 200X

FIGURE 97- 4340 STEEL VAR 48/50 HRC AT 0.0020A, 25% BROKEN PARTICLE CONTENT, ACCICULAR IMPINGEMENTS, 200X

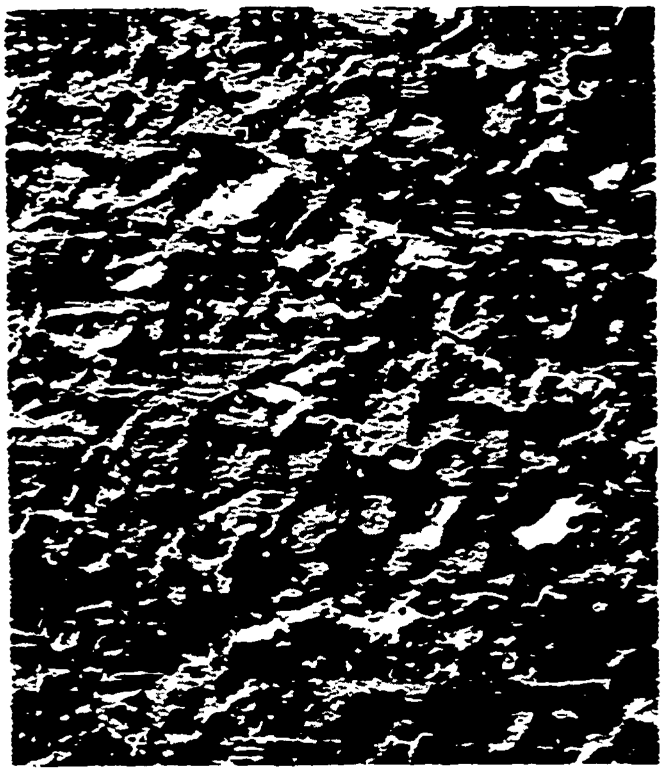


FIGURE 98- 4340 STEEL VAR 48/50 HRC AT 0.0020A, 200X 75% BROKEN PARTICLE CONTENT, SEVERE ACCICULAR IMPINGEMENTS

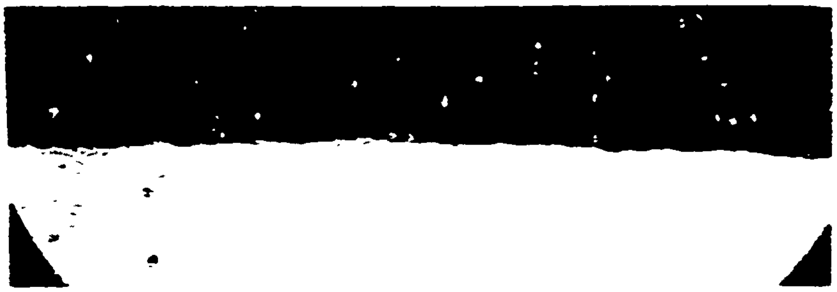


FIGURE 99- 4340 STEEL VAR 48/50 HRC AT 0.0020A AT 700X, LESS THAN 2% BROKEN PARTICLE CONTENT IN MEDIA, CONTIGUOUS SURFACE

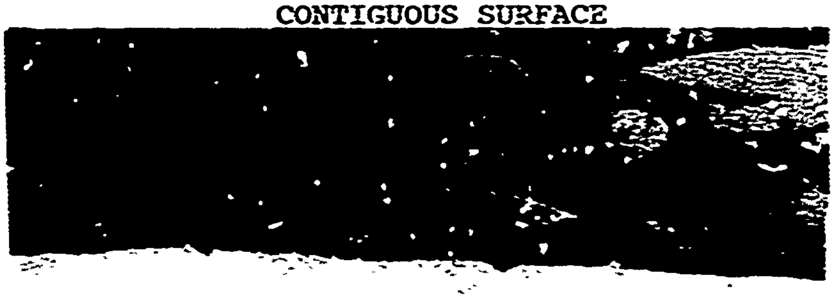


FIGURE 100- 4340 STEEL VAR 48/50 HRC AT 0.0020A AT 700X, 25% BROKEN PARTICLE CONTENT IN MEDIA, NOTICE ACCICULAR IMPINGEMENTS AND EROSION

FIGURE 101- 4340 STEEL VAR 48/50 HRC AT 0.0020A AT 700X, 50% BROKEN PARTICLE CONTENT IN MEDIA, EROSION CONTINUES

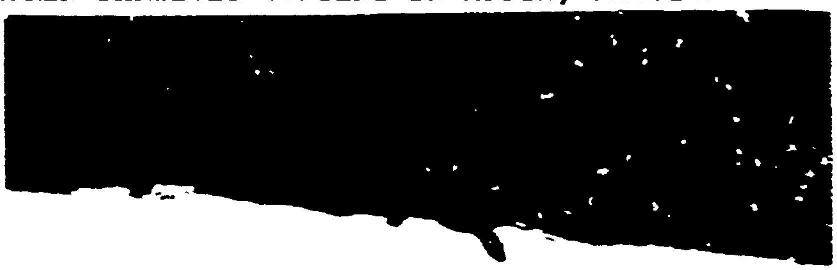
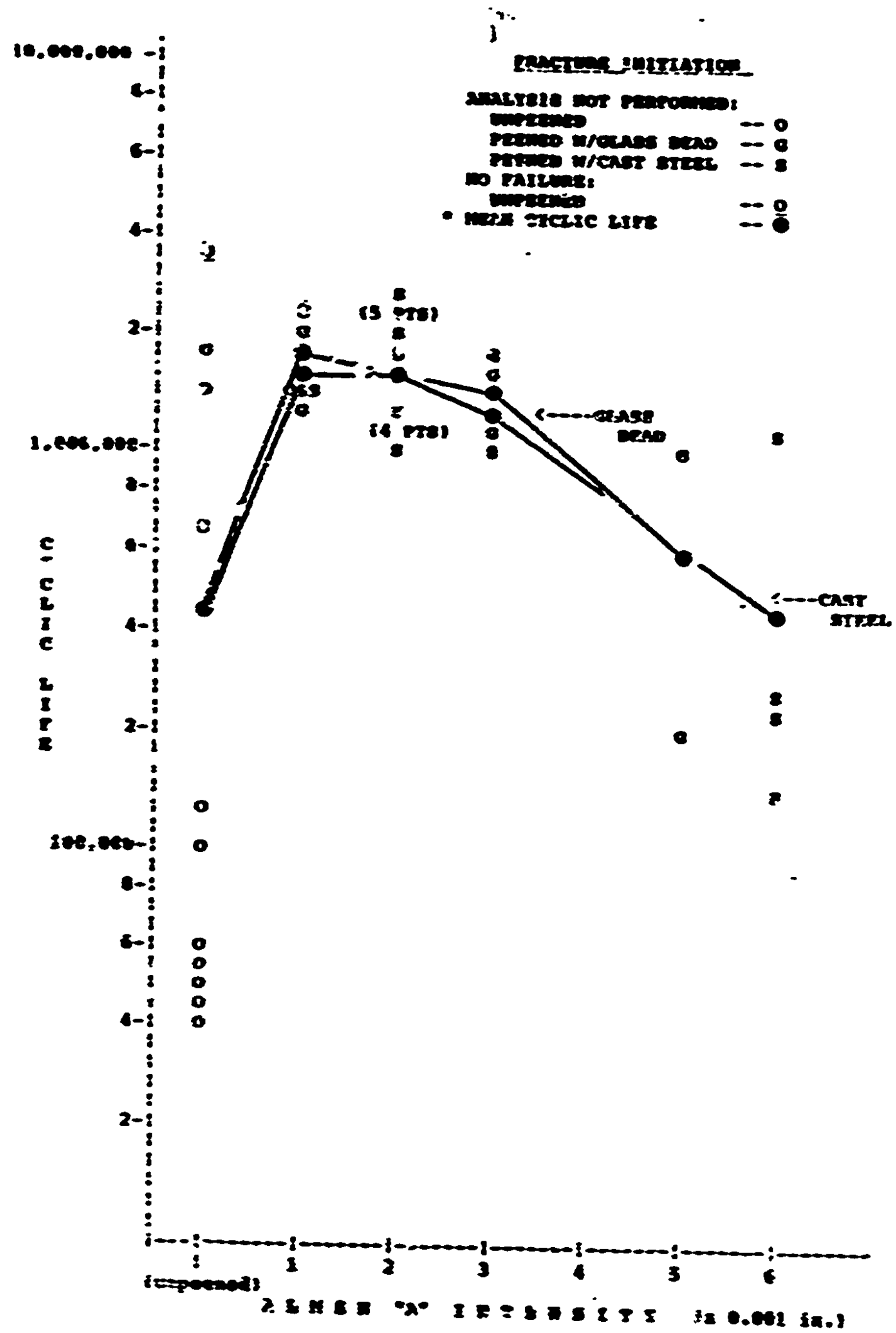


FIGURE 102- 4340 STEEL VAR 48/50 HRC AT 0.0020A AT 700X, 75% BROKEN PARTICLE CONTENT IN MEDIA, SEVERE SURFACE EROSION



*NOTE: TO ENHANCE CLARITY OF MEAN CYCLIC LIFE, ACTUAL DATA MAY HAVE BEEN DELETED. PLEASE CONSULT APPENDIX A FOR COMPLETE DATA.

TEST GROUP : FATIGUE LIFE VERSUS INTENSITY (TASK 7)
MATERIAL : 7075-T73 ALUMINUM 158 BHN (LOT C-0017)
SPECIMEN SURFACE : LATHE TURNED AND POLISHED (C)
WORKPIECE SATURATION : 100%
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 50

FIGURE 103

FATIGUE LIFE VS. INTENSITY VS. MEDIA TYPE, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 7075-T73 ALUMINUM

(3) 7075-T73 0.0100A, 0.011 dia. shot followed by 0.0030A, 0.0070 dia. shot.

(4) 7075-T6 0.0110A, 0.023 dia. shot followed by 0.0030A, 0.0070 dia. shot.

RESULTS

The major trend established is that the size of PSEF was smaller as conditions went from (1) to (4) above. There was no recognizable change in the depth of PSEF between any condition. See Figures 104 through 116 and PSEF size and depth definitions in section 4.6, the PSEF identification portion of the procedures section.

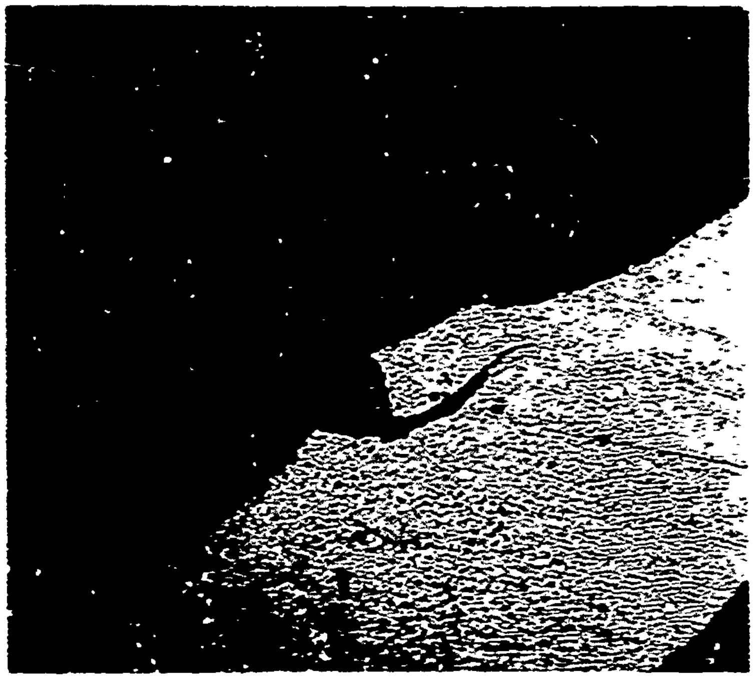


FIGURE 104- 7075-T73 AT 0.0100A AT 700X
USING 0.011" DIAMETER MEDIA, PSEF

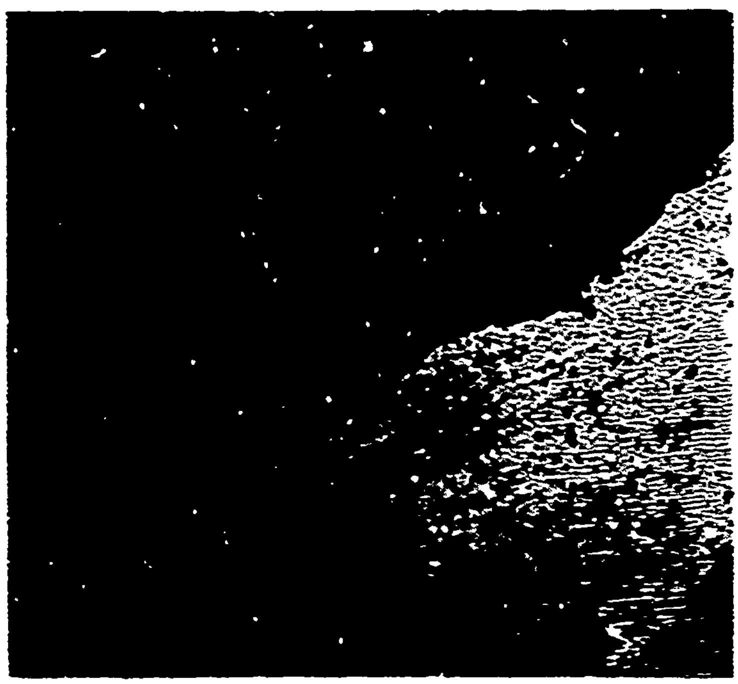


FIGURE 105- 7075-T6 AT 0.0110A AT 700X
USING 0.023" DIAMETER MEDIA, PSEF

THESE METALLOGRAPHS GRAPHICALLY PRESENT THAT USING A LARGER MEDIA AT A GIVEN INTENSITY DOES NOT PREVENT OR ERRADICATE FORMATION OF PSEF. ALTHOUGH IT DOES TO A GREAT EXTENT MASK THEIR PRESENCE FROM SURFACE OBSERVATION

7075-T73 AT 0.0100A, USING 0.011" DIAMETER MEDIA AT 700X

FIGURE 106- PSEF HAS BEEN EXTRUDED UP OFF SURFACE DUE TO OVER INTENSIFYING

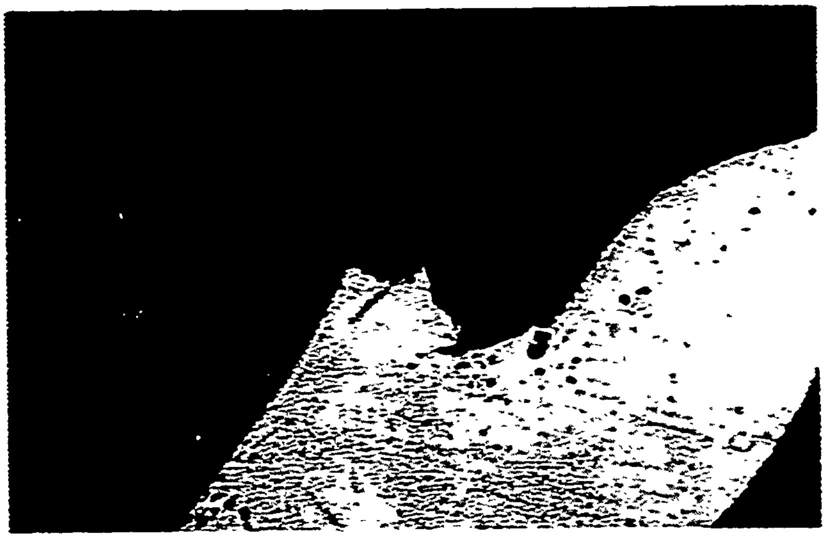


FIGURE 107- PSEF IN THE PROCESS OF BEING FOLDED OVER DUE TO SUBSEQUENT IMPACTS

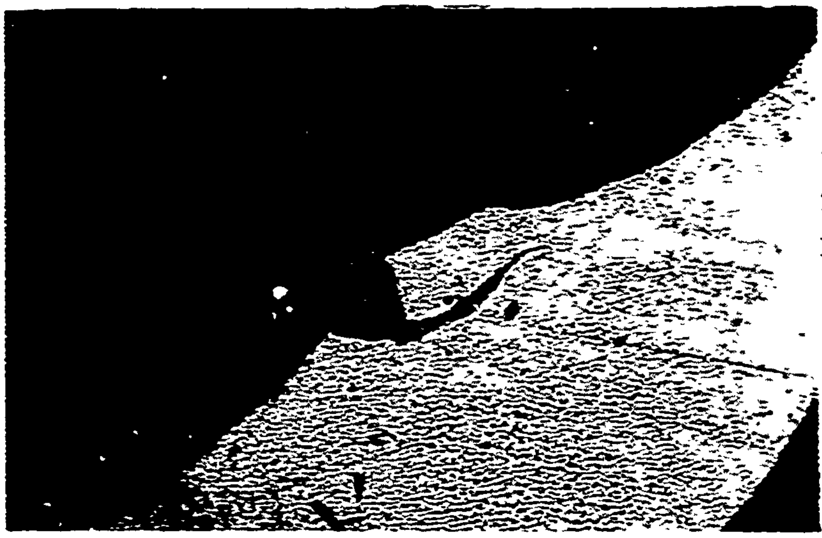


FIGURE 108- PSEF TOTALLY FOLDED OVER FORMING SUB-SURFACE ANOMALY WHICH BECOMES PRIMARY CRACK NUCLEATION SITE

7075-T73 AT 0.0100A WITH 0.011" DIAMETER MEDIA FOLLOWED BY 0.0030A WITH 0.007" DIAMETER MEDIA AT 700X

FIGURE 109- PSEF LENGTHENED AND ROUGH EDGES ROUNDED DUE TO SECOND OPERATION

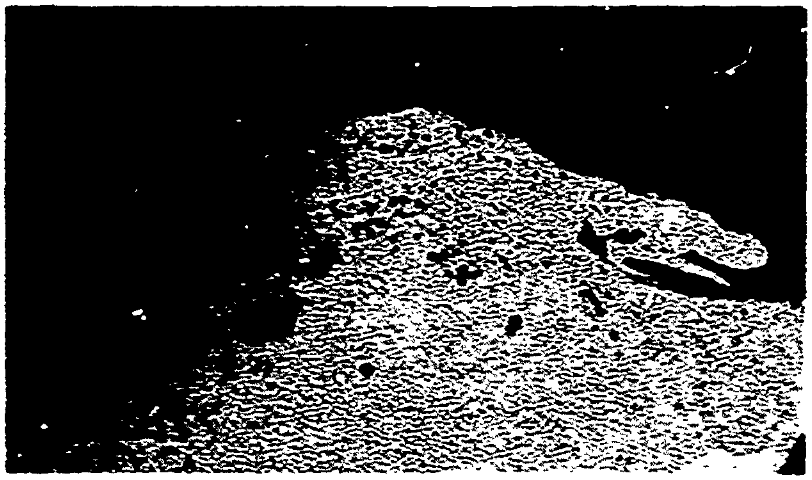


FIGURE 110- PSEF BEATEN DOWN TO CONFORM TO UNDERLYING SURFACE, VISUALLY UNDETECTABLE IN SURFACE INSPECTION

FIGURE 111- PSEF CONFORMING TO UNDERLYING SURFACE, UNDETECTABLE IN SURFACE INSPECTION

7075-T6 AT 0.0110A USING 0.023" DIAMETER MEDIA AT 700X

FIGURE 112- PSEF FORMATION AT POINT WHERE FOLDOVER HAS BEGUN

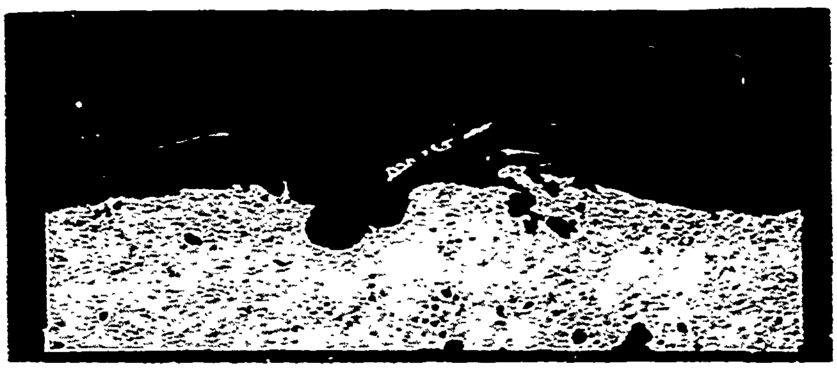


FIGURE 113- PSEF FORMATION CAUSING VOID IN SURFACE

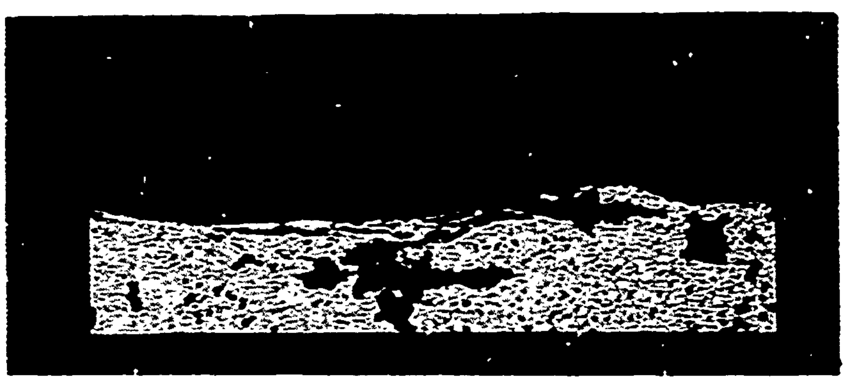


FIGURE 114- PSEF FORMATION WHERE FOLDOVER IS COMPLETE AND FURTHER EXTRUSION HAS TAKEN PLACE

7075-T6 AT 0.0110A WITH 0.023" DIAMETER MEDIA FOLLOWED BY 0.0030A WITH 0.007" DIAMETER MEDIA AT 700X

FIGURE 115- PSEF MADE TO CONFORM TO UNDERLYING SURFACE

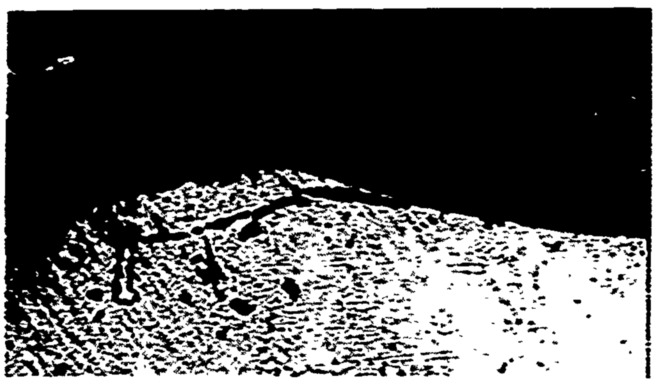


FIGURE 116- IDENTICAL SITUATION TO FIGURE 115

6.0 DISCUSSION

TASKS 1 AND 4

Task 1: Determination of workpiece saturation as a function of Almen saturation.

Task 4: Determination of the effect of saturation level on fatigue life.

GENERAL TRENDS:

Task 1 defined a relationship between workpiece hardness and peening cycle time that directly contradicts the widely held view that, all else being equal, the peening time cycle used to achieve Almen saturation represents the amount of cold working that will yield the highest fatigue resistance benefits. In fact, the underlying assumption to the use of Almen saturation as a direct determination of peening cycle time is that the Almen strip will react the same as the workpiece in terms of saturation. Clearly, this is only the case if they are the same hardness. ("A New Concept for Defining Optimum Levels of a Critical Shot Peening Process Variable," Roger Simpson, Gordon Chiasson; Second International Conference on Impact Treatment Processes, 22-26 September, 1986, p. 101.)

While being a necessary and integral step in establishing the best amount of cold work, Almen saturation calculated in such a way that it is truly representative of a workpiece's dimensions and angles of incidence vis-a-vis the peening blast is, in itself, insufficient information based on the data generated in Tasks 1 and 4.

The other benchmark currently used to establish processing time is workpiece coverage. Workpiece coverage is also necessary but insufficient information in establishing the amount of cold work required (i.e., blast cycle time) to saturate the workpiece with impingements resulting from uniform shot impacts that have masses, sizes, sphereocities, velocities and impact angles that are uniform

within small tolerances in the typical peening machine on typical production workpieces where secondary shot impacts are always present, at times in large amounts. This can be easily conceptualized when we consider the millions of shot flying around in the inside of a peening machine during a shot peening operation. There is some inevitable impacting of the workpiece surface by shot particles that have previously impacted workpiece holding fixtures, machine interior walls, and, in the case of complex shaped workpieces, other areas of the workpiece, thus resulting in lower velocity impingements. The shot impacts associated with these impingements, while increasing coverage, will obviously result in lower energy transfer to the workpiece in the form of plastic deformation. Any determination of acceptable peening cycle time which relies solely on determining the amount of the original workpiece surface obliterated by impingements bears this inherent weakness.

A common approach to mitigating the weaknesses inherent in using only Almen saturation and/or workpiece coverage is to shot peen to some predetermined minimum percentage of coverage (such as 200-percent minimum) or Almen saturation, whichever occurs last. This is utilized in several specifications the authors are aware of. While this would insure a minimum of 100-percent coverage on parts that are harder than the Almen strip, based on Task 1 results it would not insure the workpiece is saturated. This is particularly problematic when workpiece coverage becomes increasingly difficult to measure as workpieces increase in hardness above 50 Rc, the high end of the acceptable tolerance range for Almen strip hardness. In workpieces that are softer than the Almen strip, determining process cycle time by a minimum of 100-percent Almen saturation may mean that the parts

have been exposed to far more cold work than that associated with the highest fatigue resistance benefits. Materials in Task 4, particularly Ti 6AL 4, 2024-T4 aluminum, 6061-T6 aluminum and 4340 VAR, strongly indicate that a surface can be cold worked too many times. The type of surface damage from high multiples of saturation is different from PSEF. It is shallower, does not appear to be folded, but appears to be inter granular. Just as energy transfer, as defined by intensity, can be both too low or too high, so saturation versus fatigue life data indicates that the duration of exposure to that energy transfer, as defined by workpiece saturation, can be both too low and too high. Task 1 and 4 data clearly indicate that for the shot peening process to reproducibly achieve its maximum effectiveness, blast position, pattern, (i.e., nozzle or wheel position and motion vis-a-vis the workpiece, nozzle wheel wear, shot flow rate), and cycle time must be accurately controlled within tolerances known to result in certain levels of workpiece saturation known to produce the desired benefit levels.

PRACTICAL EFFECTS ON PRODUCTION SHOT PEENING:

The ramifications of having a well defined statistical relationship between Almen saturation and workpiece saturation, as a function of the relative hardness of Almen strips and the workpiece, are substantial when considering both the effectiveness of shot peening in yielding the highest possible fatigue resistance benefits and the cost associated with such processing. By determining Almen saturation achieved in a manner truly representative of the workpiece's configuration, we can statistically predict the percentage of the exposure time required to achieve Almen saturation that will

result in 100-percent workpiece saturation. As indicated by the data in Task 4, this, in itself will to a great extent focus on the correct levels of saturation.

Additionally, the use of this predictive statistical formula has large potential for reducing the cost of shot peen processing. Using, as discussed above, the widely utilized concept of a minimum of 100-percent Almen coverage or 100-percent Almen saturation, whichever occurs first, the process cycle time on some materials, such as 2024-T4, 6061-T6, 7075-T6 would be 250- to 300-percent of what was required to achieve the workpiece saturation levels associated with the highest possible fatigue benefits. In workpiece materials harder than the Almen strip, the ability to closely define 100-percent workpiece saturation can be expected to result in a dramatic reduction in the kind of process cycle time "overkill" represented by the common usage of 200- to 400-percent workpiece coverage as minimum processing requirements. If we assume that the amount of cycle time is directly related to process cost, a reduction of as much as 50-percent in the cost of processing seems realistic, depending on the mix of workpieces peened and their hardnesses. This would unequivocally justify the cost of the additional process monitoring and control devices necessary to reproduce shot flow and nozzle or wheel position, motion and blast pattern. As such, it seems probable that shot peen processing can both deliver significantly higher and more consistent benefits than it currently is at a significantly reduced cost.

TASKS 2 AND 3

Task 2: Determination of the effect of Almen intensity on fatigue life.
Task 3: Investigation of the influence of initial surface condition on fatigue life as a function of Almen intensity.

GENERAL TRENDS:

Task 2 and Task 3 data indicate that as shot peening intensity increases and regardless of workpiece surface integrity, fatigue life peaks at the point where peening intensity is sufficiently high to create PSEF which are associated with primary crack nucleation causality.

This strongly indicates that the conceptual approach to shot peening that relies only on determining the correct amount of residual stress to be imparted, and does not factor in workpiece surface integrity, is over simplified. Clearly, there is a multiplicity of action and interaction both on residual stresses and surface integrity by process variable levels that must be considered in process engineering.

A conclusion reached as early as the 1930's, and widely accepted today, is that increasingly hard materials would have increasing optimum intensities (see MIL-S-13165A and MIL-S-13165B). Based on available data (including this program) the conclusion is at times, but clearly not always, correct. The problem lies in that it is based on assumptions that give no importance to the relationship between pre processing surface condition and the resultant post-processing surface damage. Because in many cases this oversimplified and incomplete conclusion seemed to work, it has been both resilient (witness the decades that have passed since MIL-S-13165A) and highly unreliable. It has, in the author's opinion, added considerably to the current

image of shot peening being an engineering "black box" that cannot be counted on to reliably produce benefit levels required.

A logical outgrowth of the PSEF concept, and as important a finding as any in this program, is that optimum intensity range varies with pre processing surface integrity. A question arising is: if surface condition is at least or even more important than material hardness in establishing optimum intensity, how did specifications for Almen intensity in harder materials come to consistently reflect the use of relatively higher Almen intensity? The answer lies in the facts that most workpieces are not polished and a machining operation used on a relatively hard material and a relatively soft material will, all else equal, yield the same surface finish on both the hard and soft material. While there are obvious exceptions to this rule, such as tool feed rates and other machineability factors, in general this statement is correct. As stated previously, however, the same Almen intensity applied to both the harder machined workpiece and the softer machined workpiece will not yield the same amount of plastic deformation and resultant PSEF size and depth. The net effect is that higher intensities are needed to generate PSEF large enough to become primary stress concentrations and failure sites in the harder workpiece than in the softer workpiece if both are machined in the same manner.

In fact, methodology used in determining optimum intensity and other process variable optimums and tolerances during this effort has been used during and since the testing for this effort to determine similar optimum and tolerance shot peen process variable levels on a number of actual product components, including gears, aircraft and

automotive road wheels, stabilizer bars, connecting rods, turbine engine disks, and other components. Throughout these test programs, the general trend illustrated in Figure 117 has been consistent.

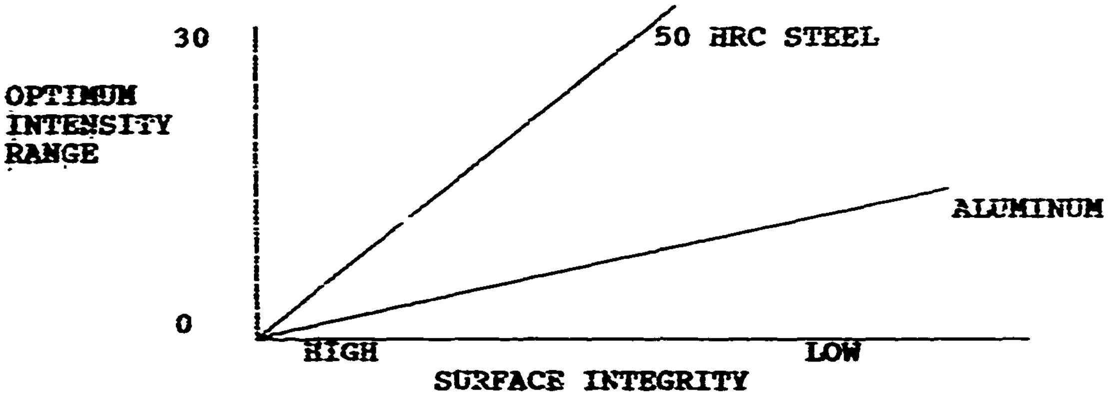


FIGURE 117: GENERAL TREND, OPTIMUM INTENSITY VERSUS PRE-PEENING WORKPIECE SURFACE INTEGRITY

PRACTICAL EFFECTS ON PRODUCTION SHOT PEENING:

The action and interaction of multiple layers of variables (material type, hardness, fracture toughness, impact angle, shot velocity, preprocessing surface integrity, etc) leave a significant amount of information and quantitative understanding to be developed and analyzed before valid intensity optimum and tolerance level prediction can be realized.

As referred to above, however, this does not leave the process engineer without methodology for determining these intensity optimum tolerance levels. With a well organized iterative testing program, these tolerances and the benefit levels associated with them, can be quantified and consistently reproduced in production.

A limiting factor to the effective prediction of workpiece saturation is the current level of acceptable inherent tolerances

associated with the Almen strip in applicable military and industry specifications. ("The Effect of Inherent Tolerances in the Almen Test Strip on Shot Peening Process Reliability," Roger Simpson, Dan Clark, and Gordon Chiasson, Third International Conference on Shot Peening, 1987.)

TASK 5: Determination of the influence of impact angle of incidence on fatigue life.

GENERAL TRENDS:

Results from Task 5 support the data from other tasks which consistently indicate that determining the effect of the process variable levels and tolerances used in shot peening on workpiece surface integrity is an important step in obtaining shot peen process benefit consistency.

It is well established that reducing impact angle at a given intensity will increase the magnitude of peak residual stresses and move the depth of maximum residual compression closer to the workpiece surface. ("A Practical Approach to Forming and Strengthening of Metallic Components Using Impact Treatment," S. Meguid, First International Conference on Shot Peening, 1981.) This increase in the magnitude of residual stresses in and near maximum PSEF depth specifically could explain why, during Phase II testing, specimens peened at low impact angles had lower fatigue life than those peened at higher impact angles, while still exhibiting internal primary crack nucleation. It alone, however, does not wholistically explain the reduction in workpiece fatigue life.

Figures 118, 119, 120, and 121 show that PSEF size and depth increased with decreasing impact angle up to and including 60 degrees for a given shot peening intensity. Figures 118 and 120 show surface cross sections of specimens peened at 90 degree angle of

impact taken transversely across the diameter of the gauge section. In Figures 119 and 121, (specimens peened at 60 degrees angle of impact, taken longitudinally across the gauge section) PSEF are largest on the rim of shot impacts which crest in the same direction as the media impact angle. The general trend for fatigue life decreasing as impact angle decreased could be explained in one, or a combination of, several ways:

(1) While primary crack nucleation was internal, secondary failures emanating from PSEF caused reduced fatigue life. There is some evidence from failure analysis that this occurred.

(2) Due to the shallower, higher magnitude compressive stresses, internally nucleated primary crack growth to the surface was significantly faster through the subsurface layer that would have been in compression at higher impact angles.

(3) Due to the reduced fracture resistance of the surfaces peened at lower impact angles, with their inherent larger and deeper PSEF, crack breakout to the surface, and subsequent total failure, was accelerated.

PRACTICAL EFFECTS ON PRODUCTION SHOT PEENING:

In actual production application, impact angle tolerances are one of the most difficult shot peen process variables to control. This is particularly true in complex shaped workpieces whose areas to be peened have relatively small radii of 60 degrees arc or more and/or multiple faces oriented in different planes and in close proximity.

At the same time, it is clear from the data, however, that impact angle is a critical variable whose actual tolerances in production

FIGURE 118- 7075-T73 ALUM., 0.0020A AT 90 DEGREE ANGLE OF IMPACT, 700X

FIGURE 119- 7075-T73 ALUM., 0.0020A AT 60 DEGREE ANGLE OF IMPACT, 700X, NOTICE "WAVE" CRESTING IN DIRECTION OF MEDIA IMPACT ANGLE (FROM UPPER RIGHT TO LOWER LEFT AT 60 DEGREES TO SURFACE)

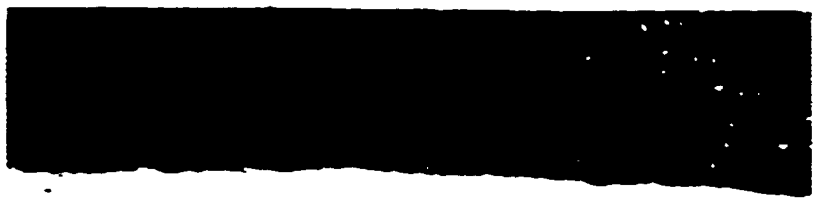


FIGURE 120- 4340 STEEL VAR 48/50 HRC, 0.0020A AT 90 DEGREE ANGLE OF IMPACT, 700X

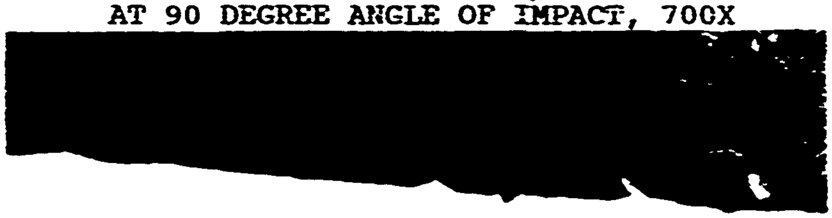


FIGURE 121- 4340 STEEL VAR 48/50 HRC, 0.0020A AT 60 DEGREE ANGLE OF IMPACT, NOTICE "WAVE" CRESTING IN DIRECTION OF MEDIA IMPACT ANGLE (FROM UPPER RIGHT TO LOWER LEFT AT 60 DEGREES TO SURFACE), 700X

must be well defined and quantitatively controlled such that established worst case fatigue life data from the lowest impact angles experienced will, indeed, be the worst case experienced in production. This argues strongly for the use of highly reproducible nozzle motion systems, which require, as a minimum, hardened gun fixtures of established and frequently calibrated dimensions. An even better, more easily controllable, but obviously more capital intensive solution, is the robotic control of nozzle motion and impact angle vis-a-vis the workpiece such that nozzle motion is programmed to follow the workpiece contour. Such equipment is currently available from peening machine manufacturers.

A pertinent point in examining Task 5 data is that Task 5 duplicated the same intensity at different impact angles. This required a manipulation of, and increase in, shot velocity at lower impact angles. In actual production, it is possible to controllably and reproducibly vary media velocity during processing through the use of closed loop feedback to air pressure, or in the case of wheel type equipment, wheel speed. The more common occurence, however, would be to have varying impact angles at the same shot velocity on a complex shaped workpiece. It is also interesting to note that, while these lower angle shot impacts will contribute to workpiece coverage, they will not contribute to workpiece saturation at an intensity specified within close tolerances and achieved with a 90-degree impact angle.

TASK 6: Determination of the effect of peening shot broken particle content on fatigue life.

GENERAL TRENDS:

There has long been a recognized trend of decreasing fatigue life with an increase in broken, angular, or shot deformed to a shape other

than approximately spherical. It has been addressed for decades in U.S. military and industry specifications.

This pattern is entirely consistent with the concept of PSEF being deleterious to fatigue life. An examination of photomicrographs of surfaces peened with varying amounts of broken shot shows that the type of surface damage imparted by shot with large percentages of broken particle content is different from that imparted by peening at intensities over optimum intensity range and/or peening at saturation levels high enough to produce surface strain cracks. See Figures 92, 93, 94, 100, 101, and 102.

PRACTICAL EFFECTS ON PRODUCTION PROCESSING:

In the real world of production processing, the control of shot is one of the most important and, concurrently, one of the most difficult tasks in consistently reproducing shot peen process benefit levels. In testing that the authors are aware of, an aircraft engine manufacturer indicated that all failures on specimens fatigue tested began at angular impingements assumed to be a result of a single broken or deformed shot impact. Peening was accomplished by a source approved by the engine manufacturer to the requirements of their then current peening specification.

At the same time, few military or industry specifications adequately address the requirements for maintaining shot spherocity. ("Quantification of Shot Peening Process Variables Affecting Workpiece Performance: Process Control and Shot Peening Media," Roger Simpson and Robert Garibay, SAE Technical Series Paper 850714). One of the reasons the authors believe that this has historically been the case is that the manufacturers of peening equipment had as their primary business, the manufacture of blast cleaning equipment. All too often,

the requirements (and equipment to meet requirements) for shot utilized in blast cleaning operations were applied "carte blanche" to shot peening applications. An example of an industry specification currently in use which makes no differentiation between these is SAE J444a, Cast Shot and Grit Size Specifications for Peening and Cleaning. While this trend has significantly improved over the past several years both in specifications and equipment available on the market, it remains perhaps the single greatest weakness in most of the shot peening applications the authors have seen. The differentiation between good shot and bad shot in MIL-S-13165B and almost all other specifications the authors are aware of is completely subjective. (Figure 7, MIL-S-13165B). In short, it is difficult to do good shot peening without good peening shot, with "good" meaning that all shot in the machine is kept as near spherical as possible. An objective performance specification for determining what are acceptable and what are unacceptable shot particles is sorely needed.

A logical alternative is cut wire shot due to its very high tensile strength and extremely high fracture resistance and durability. The limitation on cut wire shot is that it is relatively soft due to the relatively low hardness of cut wire shot necessary to cut and condition it. The inherent problems in plastically deforming the shot instead of the workpiece are evident. More insidious is that while relatively soft shot will plastically deform the relatively soft Almen strip, it will not do so on a 58/60 HRC workpiece.

Currently the most cost effective alternative for most peening applications is the rigorous control of cast steel shot quality to MIL-S-13165B, Table 1 (new shot) requirements throughout processing.

TASK 7: Determining whether peening shot type (glass beads versus steel shot) affected fatigue life in 7075-T73 aluminum.

GENERAL TRENDS:

There was no apparent difference in scatter produced by peening with either media.

PRACTICAL EFFECTS ON PRODUCTION PROCESSING:

The practical effect on production processing is significant when we consider the fracture rate of glass shot and data from Task 6. Clearly, using glass beads in production is less desirable and much more difficult to control than using cast steel media and subsequently ferrous decontaminating workpieces as necessary.

A recent alternative in the form of ceramic shot provides a viable alternative to glass. At the point of writing, ceramic shot, while considerably more expensive than glass and cast steel, has a considerably lower fracture rate than glass and not as good as cast steel.

Stainless cut wire shot has significant potential for non ferrous workpieces that are as hard or softer than the shot itself. As previously stated, while stainless cut wire is expensive, cut wire shot is by far the most durable shot that can be purchased on the market today.

TASK 8: Establishing whether increased shot size or a secondary low intensity peening affects specimen surface integrity as it relates to PSEF size and depth at a given intensity.

GENERAL TRENDS:

While both the use of larger shot at a given intensity, and the use of a second lower intensity peening in addition to, and on top of, the original peening results in smaller residual PSEF size than the

single operation, the depth of PSEF remain unchanged. (See PSEF identification in the procedures and Figures 104, 105, 109, and 115.)

PRACTICAL EFFECTS ON PRODUCTION PROCESSING:

While the use of larger shot or a second operation can improve RMS surface finish, it will not improve the basic surface integrity of the workpiece. The fatigue results of using larger shot indicate that the use of larger shot may actually degrade fatigue performance. ("Development of a Mathematical Model for Predicting the Percentage Fatigue Life Increase Resulting from Shot Peened Components - Phase I," Roger Simpson, April, 1985.)

The use of a second peening operation provides much higher surface residual compressive stresses. The authors assume this to be the greatest factor in increasing fatigue strength of components initially peened at relatively higher intensities and subsequently subjected to a second lower intensity peening. In workpieces where the inherent pre processing surface integrity is poor, and as such the optimum intensity range is high, a secondary peening operation which encapsulates surface integrity problems (i.e., machining marks, or other pre-processing surface roughness) and PSEF in a higher magnitude residual compressive stress zone would most definitely be assumed to be beneficial. For workpieces with relatively good surface integrity (i.e., finely ground or polished surfaces), the authors question the benefit that a secondary process would have due to the relatively low initial optimum intensity range.

7.0 SUMMARY

The information from Task 1 coupled with data produced in Task 4 indicates a relatively high degree of fatigue life sensitivity in some materials to the level of saturation used in shot peening, certainly much more than was previously believed.

A general pattern in specimen fatigue life as peening intensity increased was present across all material types tested in Task 2 except commerically pure titanium. While unpeened control specimens exhibited surface crack nucleation, as peening intensity increased from zero, crack nucleation became internal and specimen fatigue life increased significantly. In the case of AISI 4340 (Airmelt), the basic flaws in the material were not overcome by the benefit levels induced by shot peening. It is believed that this trend will be present for most types of metallurgical material flaws. While the peening can imbed surface flaws in a compressed layer, if these flaws are such that applied loads concentrate stresses at the flaws in sufficient magnitude, the flaws will be primary crack nucleation sites. Additionally, there is the danger that subsurface flaws will be aggravated by being imbedded in the subsurface residual tensile stress zone associated with shot peening.

At intensity levels relatively low compared to those specified in military and industry standards, fatigue life peaked for all intensity conditions tested in polished specimens. At intensity conditions above the intensity condition or range of conditions, which produced the highest fatigue life, or optimum intensity range (OIR), specimen primary crack nucleation became generally external for all material types tested. These higher than optimum intensity condition specimens also yielded fatigue life significantly lower than specimens peened at OIR.

As intensity increased, PSEF size and depth increased as can be clearly seen from the photomicrographs of surfaces cross sections for surfaces peened varying to intensity levels.

For all material types tested, except those where primary crack nucleation occured at non metallic inclusions, a PSEF was definitely identified at the primary crack nucleation site in over 90-percent of specimens peened at intensity conditions above OIR that were subjected to failure analysis. Of the remaining 10-percent, over 90-percent of these had a PSEF near enough to the crack site to be potentially causal to failure, although not definitely determined as causal to primary crack nucleation.

In less than 1-percent of these specimens, PSEF were not identified with primary crack nucleation. These specimens were all in the intensity condition just above OIR where PSEF formations were small.

This pattern of internal primary crack nucleation at low intensities and surface primary crack nucleation at higher intensities is directly opposite of what would be expected if the subsurface residual tensile stresses in the specimen were the determining factor in failure modality. The lack of this pattern is particularly significant in light of the specimens 0.200" gauge section. Clearly residual tensile stress concentration in the core of the specimen gauge sections was not a factor in failure modality.

The high degree of association of shot peen process induced surface damage (in the form of PSEF) with fatigue life failure and failure modality indicates that this phenomena is of far greater importance than has been indicated in applicable literature in the past.

The pattern of increase in OIR for varying workpiece surface conditions in Task 3 is highly significant in it's ramifications for process variable level selection in the real world of processing components to increase their fatigue strength.

It is logical that if process induced surface damage can be causal to primary crack nucleation, then the surface integrity of the part, if it has greater potential stress concentrations than the peening induces, will continue to be the determining factor to primary crack nucleation (Figure 122). This condition will exist until the plastic

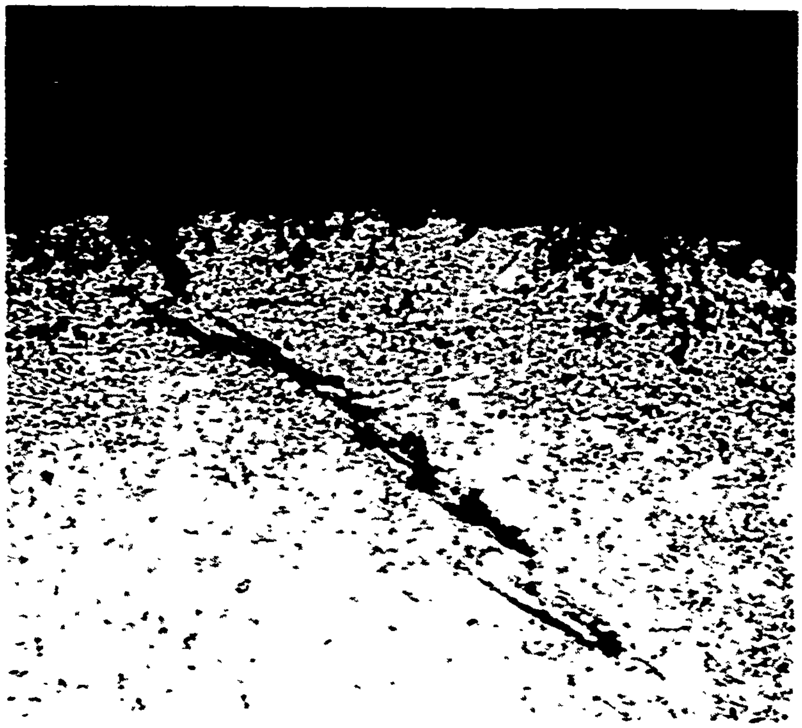


FIGURE 122 - CRACK INITIATION AT PSEF AND SUBSEQUENT INTERIOR PROPAGATION

deformation level induced by shot peening increases to the point that the process induced surface damage is great enough to displace the

pre-shot peen processing surface integrity anomalies as the determining factor to primary crack nucleation.

Quite simply, the worse a workpiece's surface integrity is before shot peening, the higher the OIR will be, with its incipient higher levels of beneficial residual compression and detrimental process induced surface damage. Until the induced surface damage becomes the weakest point in the surface from a fatigue perspective, the damage induced by the process is benign.

Another significant finding was that the fatigue life of coarser surfaced specimens peened at their respectively higher OIR was not significantly different than finely polished specimens peened at their respectively lower OIR.

It is clear that some materials, such as Ti 6Al 4V, can be extremely sensitive to saturation; and others, such as 7075-T73, may be very insensitive.

Generally, impact angle decrease was associated with decreased specimen fatigue life. This seems logical, if peening specimens at OIR, since increased media velocity (over that used in 90-degree impact angle) caused PSEF formation such that specimen fatigue life would be reduced. A 90-degree impact angle deforms the workpiece surface by moving material radially away from the center of the impact. To achieve the same intensity at 45-degree impact angle, there is a significantly greater unidirectional displacement of workpiece surface material.

The improved surface finish realized by using larger shot has been recognized by U.S. Military specifications for years. Task 8 makes it clear that this is not the case for surface integrity.

This points out the fact that profilometer examination of a

surface is insufficient information concerning measurement of changes in shot peened surface integrity. The authors see no reason to use larger shot than is necessary. In fact, Phase I data indicates that the opposite may be true.

Note the importance that, in constant amplitude testing of axial specimens as in the Phase II effort, the high cycle fatigue life being measured is a function almost entirely of crack nucleation. Because of very rapid crack propagation, with little sign of crack growth arrest, crack propagation was of little importance. While this is consistent with many actual production components, such as automotive transmission gears, crack growth rates are certainly of great importance in some transportation vehicles, such as aircraft airframe structural members. If the production application test methods are indeed representative of actual production components' physical and chemical characteristics and operational environment, the requirements for LCF and crack propagation are accounted for. The closer the testing conditions reproduce the actual operational loads and environment, the more true this will be.

Because axial fatigue specimens will show a smaller difference between the fatigue strength of peened and unpeened specimens, we should expect that the fatigue strength improvements in actual components that experience some type of bending load should be far greater than those experienced in this test program. Additionally, the effect of surface integrity degradation would tend to be greater in workpieces with bending loads due to the highest loads being at the surface. This would be expected to include the effects of broken particle content (angular impingements), the effects of intensity overpeening (PSEF), the effects of saturation overpeening (surface

strain cracking), and any other surface related phenomena.

The Phase II effort, while representing a significant milestone in development of a predictive model, does not provide engineers with such a predictive system.

The knowledge gleaned from this program, however, does not leave the process engineer without methodology for arriving at a peening process whose variable levels and tolerances have been selected through a quantitative examination of the individual and cumulative effect of process variable action and interaction on the fatigue behavior of the workpiece in question.

While requiring significant expertise and shot peen process background to perform in the most cost effective manner, the iterative system outlined below can, if implemented, achieve the production process benefit level consistency that has been almost totally lacking for decades in shot peening. It involves several straightforward steps. They are as follows:

(1) Identify the workpiece chemical and physical characteristics including material type, hardness, case depth, surface finish in the area to be peened, and other pertinent characteristics. It is important to identify the best and the worst case pre shot peening surface finish that can be expected for the area to be peened.

(2) Identify the operating environment that the workpiece in question will experience in the area to be peened. This could include:

(a) Load
 1. Type
 2. Magnitude
 3. Frequency

(b) Corrosives

(c) Damage tolerance
 1. Pre installation tolerance.
 2. Mechanical damage due to contact with foreign objects.

3. Operational contact damage with other components in the equipment in which the workpiece is installed.
4. Mechanical damage during maintenance operations.

The need for this information is related to the concept that any assumed level of acceptable operational damage tolerance can be assumed to change the optimum intensity level in the same manner that the coarser pre processing surface finish changed optimum intensity level in Task 3.

(3) Identify the prescribed intensity levels in U.S. Military and industry specifications.

(4) Insure that the process variable level controls on the peening machines intended for use during testing are sufficiently tight to give the best practicable and clearest, most succinct pattern of fatigue life at different shot peening conditions. See Table 2. It is important to note that these experimental process levels need to be substantially tighter than current industry and military specifications or than standard production peening equipment will produce. Without using very tight testing tolerances, error incumbent in variable tolerances will increase, and as such, effectively shrink acceptable production tolerance ranges. This invariably raises the cost of processing considerably (Figure 123).

(5) Establish workpiece saturation as a function of Almen saturation. ("A New Concept for defining Optimum Levels of a Critical Shot Peening Process Variable," Roger Simpson, Gordon Chiasson; Second International Conference on Impact Treatment Processes, 22-26 September, 1986, p. 101.)

(6) Determine the method of fatigue testing. Testing is best done with actual components. However, in aerospace and many other

industries, this is prohibitively expensive. Specimens which most clearly duplicate the workpiece chemical and physical characteristics and operational environment of the workpiece should be manufactured where actual production components cannot be used. Where possible, load spectrums duplicating the actual operating environment should be applied.

(7) Establish unpeened control specimen fatigue data.

(8) Manufacture an Almen test fixture which, as accurately as possible within the limitations inherent in the Almen strip, represents the workpiece and area to be peened.

(9) Shot peen a number of specimens at intensity levels varying from 0.0020A to some level above that specified in current Military and industry specifications in, 0.0020A to 0.0040A increments.

(10) From step 9 data, establish general trends in fatigue life as intensity increases.

(a) If fatigue life is highest at the highest intensity peened, peen at higher intensities and fatigue test these specimens. Repeat this until fatigue life begins to decrease for higher intensity.

(b) When fatigue life has peaked at some intensity value between 0.0020A and the highest intensity, shot peen several specimens at intensities above and below the intensity associated with the highest statistical fatigue life in 0.0005A intensity increments to quantitatively define the exact position of OIR (Optimum Intensity Range) and its tolerances.

(11) Using the optimum intensity level as defined in 10, define in a similar manner the optimum workpiece saturation level, effect on

fatigue life of changing impact angle, and other process variable tolerance quantitative effects.

(a) Define the S/N curve for unpeened specimens and specimens at optimum intensity and saturation levels.

(12) Production implementation should follow this basic procedure:

Production Processing:

(a) Now that an optimum intensity range has been generated through peening and testing per steps 10 and 11, establish acceptable production peening variable tolerance ranges which will affect the optimum intensity range. This should be done in a procedure similar to the following:

(1) Determine the tolerance ranges for each variable defined in step 11.

(2) Add up the cumulative tolerances for all variables, best case and worst cast, and tailor the optimum intensity range as to how these factors would affect it (Figure 123).

(3) Determine the calibration tolerances of the monitors and meters used for monitoring and controlling those critical variables and tailor the optimum intensity range again to reflect their effect (Figure 123).

(b) Establish cumulative tolerance condition S/N curve variance with fatigue test specimens peened with conditions duplicating the cumulative top and bottom of the process variable tolerance ranges.

What this procedure does, in effect, is to shrink the acceptable optimum intensity range which can be reproduced

on existing equipment so as to insure that processing is always maintained within acceptable limits.

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    |<--------------------W--------------------->|
    |                                            |
--->| X     |<---                    --->|    X  |<---
    |       |                            |       |
    | --->|Y |<---                --->| Y|<---   |
    |       |   |  |               |  |  |       |
    |       |->| V|<---        --->|V |<-|       |
    |       |   |  |               |  |  |       |
    |          |  |<-------Z------>|  |          |
    |             |                |             |
<---------------ALMEN INTENSITY CONTINUUM---------------->
```

V - ALMEN STRIP CUMULATIVE TOLERANCES
W - OPTIMUM INTENSITY RANGE AS DEFINED BY STEPS 10 AND 11
X - CRITICAL VARIABLE CUMULATIVE TOLERANCES EFFECT ON OPTIMUM INTENSITY RANGE
Y - CRITICAL VARIABLE PROCESS CONTROLS CALIBRATION TOLERANCES
Z - PRODUCTION INTENSITY RANGE SPECIFICATION

FIGURE 123 - CONCEPTUAL ILLUSTRATION FOR ARRIVING AT PRODUCTION PROCESS TOLERANCE SPECIFICATION

(c) Design and implement production equipment and process controls that can quantitatively reproduce these process variable levels.

(d) Determine what level of inherent Almen strip cumulative tolerances will be specified for production processing. ("The Effect of Inherent Tolerances in the Almen Strip on Shot Peening Process Reliability," Roger Simpson, Dan Clark, Gordon Chiasson; Third International Conference on Shot Peening, 1987) These tolerances should also be removed from

the acceptable production tolerance range.

(e) Thoroughly educate process engineering personnel, production supervisors, operators, quality assurance personnel, maintenance personnel,and others as applicable, as to the difference between this type of peening operation and traditional "controlled" shot peening. One should carefully describe how changes in single or multiple variable levels will statistically affect the level of benefit the process induces in workpieces.

(f) Utilize the information in (a) and (b) to quantitatively decide disposition of components rejected for out of tolerance processing.

When approached from the standpoint of scientifically defining what the shot peen variables are that affect workpiece performance for the workpiece in question, and what the correct levels and tolerances of each variable are such that their net effect on fatigue life at the high and low cumulative tolerance levels is to provide the needed fatigue strength benefits, the shot peening process has an extremely high benefit/cost ratio. What is left then is to clearly define process variable tolerance controls and implement the fatigue strength benefits into the real world of production components.

The need for updated military and industry specifications is clear in light of the data.

The area of process control is currently seeing some significant attention in terms of proposed Military and AMS standards.

Of particular concern, however, is the ongoing lack of attention in Military and industry standards to choosing the correct process

levels to be controlled to. Indeed, the very idea of a need for process control argues that some levels of process variables are better than others. It is far more logical to outline in standards how to quantitatively ascertain what the right process variable levels are than to arbitrarily choose to include tables of specified intensity for no better reason than because they have always been there. Controlling at very fine tolerances to the wrong nominal level is, at best problematic. Tighter control is only "good" if it can be documented to provide benefit for the added cost. The question is how to know if the nominal level and tolerances you are controlling to are the correct ones unless there is hard data to support it. Once that question is addressed in a quantitative fashion, with quantitative effects documented for variance in all the critical variables, implementing process equipment, process controls, and written specifications becomes a matter of what benefit levels are desired and the cost associated with achieving them.

The real world ramifications for the use of the methodology outlined above is the capability to significantly and reliably increase the allowable load on fatigue sensitive workpieces. In the past, while significant increases were possible under laboratory conditions, achieving fatigue benefit reliability induced by the process was often elusive. The authors have utilized this methodology extensively in production applications and have seen significant load capacity increases on actual production components.

Using this methodology for applying shot peening as part of the original design strength of a workpiece will probably not be widely cost effective until a predictive model for optimum process variable levels and tolerances can be easily computer applied.

The use of this type of iterative test methodology is, however, highly cost effective when seeking to increase the load capacity of existing components and component systems. This is true largely because of the fact that shot peening usually can be applied to a component with little or no redesign of that component. An engineer can select the weak points on a component or the weakest components in a system and upgrade the performance of the whole. This is in contrast to the large redesign and/or retooling costs that would be associated with making a basic change in part design, without acounting for the other associated risks and validation testing costs incumbent on redesign. While the use of better materials is at times the most expeditious option in increasing allowable loads, in aerospace the very best is often already being used; and in automotive the cost of using better materials often proves cost prohibitive.

In cases of applying a fix for an emergency situation that involves little time to retool or reengineer, the methodology described above is an outstandingly efficient tool to effectively increase the load carrying capacity of a component. And it can be done in a matter of a few weeks.

The risks involved in using the shot peen process to deliver some minimum level of benefit, without going through the type of variable optimum and acceptable tolerance identification methodology outlined are both large and insidious. Shot peening has a history of promising things in laboratory test results that are not fulfilled in production due to a lack of understanding of the interaction of the process on the specific workpiece in question. Clearly, scrimping on the fatigue test budget in this case is not cost effective if a certain minimum level of process benefit is required.

8.0 RECOMMENDATIONS FOR FURTHER STUDY

The test conditions utilized in Phase I and Phase II of this program were chosen for their capacity to isolate the effects of process induced surface integrity phenomena from other critical variable actions and interactions on workpiece fatigue strength. Variables such as notch effect, applied load stress concentration factors, and process induced residual stress profile are examples. These other factors, many of which are well documented in technical literature, are indeed critical variables that must be considered when defining optimum process variable nominal and range values for actual production component shot peen processing. They can be, however, and as indicated by the data, inextricably linked with the level of shot peen process induced surface integrity degradation from any given level of shot peen processing in their cumulative effects on workpiece fatigue strength. It is important to note that the authors in no way suggest using the optimum shot peen process variable values defined for the test conditions of either Phase I or Phase II of this program as universal prescription for intensity optimums on the material types investigated. The workpiece chemical and physical characteristics and the particulars of the operational load and operating environment for the workpiece in question must be taken into consideration.

The relationships of interaction between applied load stress concentration factors, shot peen process induced residual stress profile, workpiece material characteristics (such as fracture toughness and many others), and both pre and post process surface integrity are complex and have yet to be statistically quantified. While Phase I and Phase II of this research program have added significantly to the understanding of how process induced surface

integrity degradation affects workpiece fatigue life, substantially more data is needed in defining all of the critical variable relationships before these relationships can be predictively understood and applied on production components at the engineering design stage of their manufacture.

Clearly, however, the data generated in the Phase I and Phase II efforts contradicts the broadly accepted assumption that the shape in profile of the shot peen process induced residual stress pattern is the sole primary determining factor, or even the sole determining factor, to the quantitative position of optimum process variable values. In the authors' opinion, this assumption is flawed at best, and is quite probably a dangerous autonomous criteria on which to base specific component shot peen process variable optimization.

The next phase of this research program, well underway at the time of the writing of this report, addresses the determination of optimum shot peen process variable quantitative values when factoring the interaction of workpiece shape and applied load stress concentration characteristics into the current data base concerning the effects of variance of workpiece surface integrity as shot peen process variable quantitative values change. It also addresses how maximum acceptable operational damage tolerance and several other criteria statistically relate to the whole of workpiece, process, and loading variables.

Until such time as the data base required to compile the predictive mathematical model envisioned by this multiphase program is available, determination of optimum process variable nominal and range values and the resultant fatigue strength benefits derived for any given workpiece of given chemical, physical, and operational load

characteristics can be made only through a battery of iterative tests which both duplicates the operational load characteristics and workpiece characteristics for the specific workpiece in question, and does so for varying quantitative levels of shot peen processing.

An important realization that should be derived from the Phase I and Phase II data as well as other technical publications, is that the very simple charts that can be found in a majority of military and industry specifications listing prescribed peening intensity ranges are clearly inadequate for prescribing shot peen process levels which can be relied on to consistently produce the desired benefit level on workpieces of all configurations and loading characteristics. If one intends to use the shot peen process as a means of reliably reproducing certain desired levels of workpiece fatigue strength benefit, several factors above and beyond material type and hardness must be considered. While elegant in their simplicity, arriving at optimal shot peen parameter values and insuring that the desired benefit level is attainable at both extremes of cumulative acceptable process variable tolerance limits is technically a much more complex challenge than the typical military and/or industry specification's table of prescribed peening intensities would indicate.

An additional area that needs further development is that of process measurement. As described earlier and in numerous publications, the Almen test strip system is quite incapable of being the sole and autonomous measure of shot peen process effectiveness as it is currently prescribed in military and industry specifications. It is obvious from a simple analysis of cumulative acceptable tolerances that the Almen test strip's currently acceptable tolerances will exceed the specified intensity ranges in these same specifications.

VARIABLE	TOLERANCE
Almen Strip Hardness Variation (6HRC)	+/-0.0005
Almen Strip Thickness	+/-0.0010
Almen Strip Flatness	+/-0.0010
Almen Gauge Mounting Plane	+/-0.0020
Almen Gauge Indicator Graduation	+/-0.0005
CUMULATIVE TOLERANCES	+/-0.0050

SUMMARY OF MINIMUM CUMULATIVE ARC HEIGHT VARIABILITY OF CURRENTLY ALLOWABLE TOLERANCES IN TYPICAL U.S. MILITARY AND INDUSTRY SPECIFICATIONS

A significant improvement in the current Almen test strip system can be accomplished by merely reducing acceptable tolerances inherent in Almen test strips. This can be done without changing its basic structure or configuration. The Almen test strip system, however, is currently and will remain for the forseeable future, a necessary but insufficient measurement of process effectiveness and reproducibility. Further research on nondestructive process effectiveness measurement is needed.

APPENDIX A

TABLE A-1

FATIGUE RESULTS VS. INTENSITY, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR TITANIUM (C.P.)

PEENED/ UNPEENED	MEDIA SIZE/TYPE	CYCLES TO FAILURE (Nf x 1000)	MEAN $\bar{X}$	FRACTURE INITIATION (# OF SPEC.) INT.	EXT
BASELINE (UNPEENED)	N/A	72, 80, 80, 122, 180, 237	129	N/A	N/A
0.0010A	MIL-13/ GLASS BEAD	60, 78	69	N/A	N/A
0.0020A	MIL-13/ GLASS BEAD	81, 92, 96	90	N/A	N/A
0.0030A	MIL-11/ GLASS BEAD	63, 65, 69	66	N/A	N/A
0.0050A	MIL-8/ GLASS BEAD	40, 43, 60	48	N/A	N/A
0.0120A	MIL-5/ GLASS BEAD	26, 35, 41	34	N/A	N/A

TEST GROUP : FATIGUE LIFE VERSUS INTENSITY (TASK 2)
MATERIAL : TITANIUM (C.P.) 34/36 HRC, (LOT C-0016)
SPECIMEN SURFACE : LATHE TURNED & POLISHED (C)
WORKPIECE SATURATION : 100%
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 85.3

APPENDIX A

TABLE A-2

FATIGUE RESULTS VS. INTENSITY, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 6AL - 4V TITANIUM

INTENSITY CONDITION	MEDIA SIZE/TYPE	CYCLES TO FAILURE (N_f x 1000)	MEAN $\bar{X}$	FRACTURE INITIATION (# OF SPEC.) INT.	EXT
BASELINE (UNPEENED)	N/A	61, 64, 83, 134, 185, 214, 5711	922	N/A	N/A
0.0010A	MIL-13/ GLASS BEAD	109, 941	525	N/A	N/A
0.0015A	S-70/ CAST STEEL	2031, 2131	2081	N/A	N/A
0.0020A	MIL-13/ GLASS BEAD	1179, 1471, 2523, 1753, 1732, 1656, 3754	2010	N/A	N/A
0.0025A	S-70/ CAST STEEL	960	N/A	N/A	N/A
0.0030A	MIL-11/ GLASS BEAD	113, 1499	544	N/A	N/A
0.0030A	S-70/ CAST STEEL	19		N/A	N/A
0.0040A	MIL-9/ GLASS BEAD	118, 612, 1199	643	N/A	N/A
0.0050A	MIL-8/ GLASS BEAD	82, 92, 198	124	N/A	N/A
0.0120A	MIL-5/ GLASS BEAD	19, 34, 36	30	N/A	N/A

TEST GROUP : FATIGUE LIFE VERSUS INTENSITY (TASK 2)
MATERIAL : 6AL - 4V TITANIUM 41/42 HRC (LOT C-0015)
SPECIMEN SURFACE : LATHE TURNED & POLISHED (C)
WORKPIECE SATURATION : 100%
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 140

APPENDIX A

TABLE A-3

FATIGUE RESULTS VS. INTENSITY, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 2024-T4 ALUMINUM

INTENSITY CONDITION	MEDIA SIZE/TYPE	CYCLES TO FAILURE (Nf x 1000)	MEAN $\bar{X}$	FRACTURE INITIATION (# OF SPEC.) INT.	EXT
BASELINE (UNPEENED)	N/A	184, 162, 141, 138, 186, 129	157	0	6
0.0010A	MIL-13/ GLASS BEAD	1110, 293, 1235, 947	879	2	N/A
0.0020A	MIL-13/ GLASS BEAD	162, 110, 482	251	2	1
0.0030A	MIL-11/ GLASS BEAD	112, 111, 82	102	2	1
0.0050A	MIL-8/ GLASS BEAD	84, 128, 110	107	0	3
0.0100A	MIL-5/ GLASS BEAD	135, 116, 113	121	0	3
0.0120A	MIL-5/ GLASS BEAD	89, 73, 91	84	0	3
0.0140A	MIL-4/ GLASS BEAD	69, 94, 92	85	0	3

TEST GROUP : FATIGUE LIFE VERSUS INTENSITY (TASK 2)
MATERIAL : 2024-T4 ALUMINUM 110/119 HBN (LOT C-0001)
SPECIMEN SURFACE : LATHE TURNED & POLISHED (C)
WORKPIECE SATURATION : 100%
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 47

APPENDIX A

TABLE A-4

FATIGUE RESULTS VS. INTENSITY, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 6061-T6 ALUMINUM

INTENSITY CONDITION	MEDIA SIZE/TYPE	CYCLES TO FAILURE (Nf x 1000)	MEAN $\bar{X}$	FRACTURE INITIATION (# OF SPEC.) INT.	EXT
BASELINE (UNPEENED)	N/A	64, 447, 224, 158, 130, 412	239	N/A	N/A
0.0010A	MIL-13/ GLASS BEAD	940, 1054, 931, 490, 648	813	N/A	N/A
0.0030A	MIL-11/ GLASS BEAD	448, 431, 310	396	N/A	N/A
0.0050A	MIL-8/ GLASS BEAD	173, 164, 161	166	N/A	N/A
0.0080A	MIL-5/ GLASS BEAD	181, 124	153	N/A	N/A
0.0100A	MIL-5/ GLASS BEAD	124, 126, 114	121	N/A	N/A
0.0120A	MIL-5/ GLASS BEAD	88, 101, 106, 85, 90, 74	91	N/A	N/A
0.0140A	MIL-4/ GLASS BEAD	124, 118, 77	106	N/A	N/A

TEST GROUP : FATIGUE LIFE VERSUS INTENSITY (TASK 2)
MATERIAL : 6061-T6 ALUMINUM 93/100 HBN (LOT C-0003)
SPECIMEN SURFACE : LATHE TURNED & POLISHED (C)
WORKPIECE SATURATION : 100%
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 40

TABLE A-5

FATIGUE RESULTS VERSUS INTENSITY AND PEENING PARAMETERS FOR 7075-T6 ALUMINU PHASE I

INTENSITY CONDITION	MEDIA TYPE	CYCLES TO FAILURE (Nf x 1000)	MEAN X	FRACTURE INITIATIO (# OF SPE INT.	EXT
BASELINE (UNPEENED)	N/A	111, 359, 154, 252	219	0	3
0.0010A	GLASS BEAD	628, 702, 654, 612, 649, 729, 577	650	1	0
0.0030A	GLASS BEAD	777, 847, 795, 632, 670, 716, 633, 569, 607	694	0	0
0.0050A	GLASS BEAD	691, 699, 553, 601, 639, 653, 616, 338, 584	597	0	0
0.0070A	GLASS BEAD	470, 591, 527, 582, 573, 616	560	0	2
0.0090A	GLASS BEAD	551, 597, 622, 606, 533, 574, 567, 460, 509	558	0	1
0.0110A	GLASS BEAD	477, 609, 592, 555, 575, 535, 504	550	0	3
0.0130A	GLASS BEAD	538, 566, 466	523	2	1
0.0150A	GLASS BEAD	516, 454, 498	489	1	2
0.0200A	GLASS BEAD	406, 261, 193	287	0	2

MATERIAL : 7075-T6
SPECIMEN SURFACE : LATHE TURNED AND POLISHED
WORKPIECE SATURATION : 100%
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 58 KSI
GAGE SECTION DIA. : 0.375"

APPENDIX A

TABLE A-6

FATIGUE RESULTS VS. INTENSITY, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 7075-T6 ALUMINUM

INTENSITY CONDITION	MEDIA SIZE/TYPE	CYCLES TO FAILURE (Nf x 1000)	MEAN $\overline{X}$	FRACTURE INITIATION (# OF SPEC.) INT.	EXT
BASELINE (UNPEENED)	N/A	84, 99, 82, 217, 197, 93	129	N/A	N/A
0.0010A	MIL-13/ GLASS BEAD	298, 275, 360, 323, 357, 383	333	N/A	N/A
0.0030A	MIL-11/ GLASS BEAD	255, 257, 206	239	N/A	N/A

TEST GROUP : FATIGUE LIFE VERSUS INTENSITY (TASK 2)
MATERIAL : 7075-T6 ALUMINUM 143 HBN (LOT C-0002)
SPECIMEN SURFACE : LATHE TURNED & POLISHED (C)
WORKPIECE SATURATION : 100%
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 58

APPENDIX A

TABLE A-7

F?TIGUE RESULTS VS. INTENSITY, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 7075-T73 ALUMINUM

INTENSITY CONDITION	MEDIA SIZE/TYPE	CYCLES TO FAILURE (Nf x 1000)	WEIBULL W	MEAN $\overline{X}$	FRACTUR INITIATI (# OF SPE INT.	EX
BASELINE (UNPEENED)	N/A	66, 24, 34, 112, 47	4.373	57	N/A	5
0.0010A	S-70/ CAST STEEL	1275, 1544, 29, 1424, 1236	N/A	1102	1	4
0.0020A	S-70/ CAST STEEL	2805, 1811,2093,1176, 1822, 1096	291	1800	7	0
0.0040A	S-70/ CAST STEEL	346, 323, 1348, 1463, 588, 120, 141, 1489	43	727	5	3
0.0060A	S-70/ CAST STEEL	137, 128, 118, 116, 107, 105, 196	77	130	0	7
0.0080A	S-70/ CAST STEEL	95, 131, 105, 88,126, 89, 81, 104	67	102	0	8
0.0100A	S-70/ CAST STEEL	62, 91, 98, 101, 91, 104, 68, 109	27	91	0	8
0.0140A	S-70/ CAST STEEL	93, 112, 37, 112,120, 94, 46, 86	8	88	0	8

TEST GROUP: FATIGUE LIFE VERSUS INTENSITY (TASK 2)
MATERIAL: 7075-T73 ALUMINUM 136 HBN (LOT C-0030)
SPECIMEN SURFACE : LATHE TURNED & POLISHED (C)
WORKPIECE SATURATION : 100%
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 50

APPENDIX A

TABLE A-8

FATIGUE RESULTS VS. INTENSITY, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 4340 AIRMELT STEEL 20/25 HRC

INTENSITY CONDITION	MEDIA SIZE/TYPE	CYCLES TO FAILURE (Nf x 1000)	MEAN $\bar{X}$	FRACTURE INITIATION (# OF SPEC.) INT.	EXT
BASELINE (UNPEENED)	N/A	325, 277, 175, 189, 272, 182	237	0	6
0.0020A	S-70/ CAST STEEL	118, 48	83	0	2
0.0030A	S-70/ CAST STEEL	345, 218, 659, 372, (R/O)	399	0	4
0.0035A	S-70/ CAST STEEL	444, 425, 146	338	0	2
0.0040A	S-70/ CAST STEEL	484, 438, (R/O), 887, 408 915	626	1	4
0.0045A	S-70/ CAST STEEL	498, 493, 333, (R/O)	441	0	3
0.0050A	S-70/ CAST STEEL	640	N/A	0	1
0.0060A	S-70/ CAST STEEL	130, 102, 356 (R/O), 196	196	0	3
0.0075A	S-70/ CAST STEEL	452, 556	504	0	2
0.0090A	S-70/ CAST STEEL	(R/O), 240	N/A	0	1
0.0100A	S-70/ CAST STEEL	639, 543, 827	670	0	3
0.0110A	S-110/ CAST STEEL	106, 131	119	0	2
0.0120A	S-110/ CAST STEEL	141, 176, 236	184	0	3

TEST GROUP : FATIGUE LIFE VERSUS INTENSITY (TASK 2)
MATERIAL : 4340 AIRMELT STEEL 20/25 HRC (LOT C-0006)
SPECIMEN SURFACE : GROUND AND POLISHED (C)
WORKPIECE SATURATION : 100%
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 102

APPENDIX A

TABLE A-9

FATIGUE RESULTS VERSUS INTENSITY, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 4340 AIRMELT STEEL 34/36 HRC

INTENSITY CONDITION	MEDIA SIZE/TYPE	CYCLES TO FAILURE (Nf x 1000)	MEAN $\bar{X}$	FRACTURE INITIATION (# OF SPEC.) INT.	EXT
BASELINE (UNPEENED)	N/A	169, 135, 103, 103	128	0	4
0.0030A	S-70/ CAST STEEL	108, 113, 77	99	0	3
0.0035A	S-70/ CAST STEEL	351, 697, (R/O)	524	1	1
0.0040A	S-70/ CAST STEEL	280, 249, 358	296	0	3
0.0045A	S-70/ CAST STEEL	(R/O), 3336	N/A	1	0
0.0050A	S-70/ CAST STEEL	880, (R/O)	N/A	1	0
0.0055A	S-70/ CAST STEEL	136, 196	166	0	2
0.0060A	S-70/ CAST STEEL	75, 2112, 219, (R/O) (R/O), 3710	1529	2	2
0.0065A	S-70/ CAST STEEL	107, 176, 277	187	0	3
0.0070A	S-70/ CAST STEEL	120, 136	128	0	2
0.0075A	S-70/ CAST STEEL	378, 205	292	0	2
0.0090A	S-70/ CAST STEEL	52, 68, 94	71	0	3
0.0120A	S-110/ CAST STEEL	118, 88, 77	94	0	3

TEST GROUP : FATIGUE LIFE VERSUS INTENSITY (TASK 2)
MATERIAL : 4340 AIRMELT STEEL 34/36 HRC (LOT C-0007)
SPECIMEN SURFACE : GROUND & POLISHED (L)
WORKPIECE SATURATION : 100%
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 140

APPENDIX A

TABLE A-10

FATIGUE RESULTS VERSUS INTENSITY, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 4340 AIRMELT STEEL 40/42 HRC

INTENSITY CONDITION	MEDIA SIZE/TYPE	CYCLES TO FAILURE (Nf x 1000)	MEAN $\bar{X}$	FRACTURE INITIATION (# OF SPEC.) INT.	EXT
BASELINE (UNPEENED)	N/A	241, 143, 93	159	0	3
0.0030A	S-70/ CAST STEEL	661, 797, 478, (R/O), (R/O), 1237	793	3	1
0.0035A	S-70/ CAST STEEL	(R/O), (R/O), (R/O) (R/O), (R/O), 1133	N/A	N/A	N/A
0.0040A	S-70/ CAST STEEL	(R/O), (R/O), (R/O) (R/O), (R/O), (R/O)	N/A	N/A	N/A
0.0045A	S-70/ CAST STEEL	(R/O), 968, (R/O), 1393 (R/O), (R/O)	1181	1	N/A
0.0050A	S-70/ CAST STEEL	463, (R/O), (R/O), (R/O), 137	300	N/A	1
0.0055A	S-70/ CAST STEEL	1143, 419, 971, 535, 1464	906	4	1
0.0060A	S-70/ CAST STEEL	2084, 1594, 1980, (R/O), (R/O), (R/O), 209	1467	2	1
0.0065A	S-70/ CAST STEEL	155, 899, 520, 144, 2065	757	3	2
0.0070A	S-70/ CAST STEEL	(R/O), 67, 99, 2936, 77	795	N/A	2
0.0075A	S-70/ CAST STEEL	1601, (R/O)	N/A	N/A	1
0.0080A	S-70/ CAST STEEL	281, 329	305	1	N/A
0.0090A	S-70/ CAST STEEL	566, 265, 47	293	0	3
0.0120A	S-110/ CAST STEEL	102, 526, 337	322	0	3

TEST GROUP : FATIGUE LIFE VERSUS INTENSITY (TASK 2)
MATERIAL : 4340 AIRMELT STEEL, 40/42 HRC (LOT C-0020)
SPECIMEN SURFACE : GROUND & POLISHED (L)
WORKPIECE SATURATION : 100%
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 155

APPENDIX A

TABLE A-11

FATIGUE RESULTS VERSUS INTENSITY, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 4340 AIRMELT STEEL 48/50 HRC

INTENSITY CONDITION	MEDIA SIZE/TYPE	CYCLES TO FAILURE (Nf x 1000)	MEAN $\bar{X}$	FRACTURE INITIATION (# OF SPEC INT.	EXT
BASELINE (UNPEENED)	N/A	61, 97, 46, 48, 70, 93, 106	74	0	7
0.0030A	S-70/ CAST STEEL	337, 754, 408	500	1	2
0.0060A	S-70/ CAST STEEL	267, 574, 413	418	2	1
0.0065A	S-70/ CAST STEEL	441, 261	351	1	1
0.0070A	S-70/ CAST STEEL	1164, 436, 304	635	2	1
0.0075A	S-70/ CAST STEEL	1138, 982, 804, 2047, 203, 364, 476	859	4	3
0.0080A	S-70/ CAST STEEL	934, 495, 225, 478,1037, 311, 791, 719, 795, 758, 685, 1019, 1113	720	7	6
0.0085A	S-70/ CAST STEEL	590, 629, 370, 122, 743	491	3	2
0.0090A	S-70/ CAST STEEL	649, 191, 702, 536	520	2	2
0.0095A	S-70/ CAST STEEL	324, 269, 314, 238	286	2	2
0.0105A	S-110/ CAST STEEL	593, 388	491	0	2
0.0120A	S-110/ CAST STEEL	175, 326, 522, 473	374	3	1

TEST GROUP : FATIGUE LIFE VERSUS INTENSITY (TASK 2)
MATERIAL : 4340 AIRMELT STEEL 48/50 HRC (LOT C-0021)
SPECIMEN SURFACE : GROUND AND POLISHED (L)
WORKPIECE SATURATION : 100%
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 170

APPENDIX A

TABLE A-12

FATIGUE RESULTS VERSUS INTENSITY, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 4340 VACUUM ARC REMELT STEEL 48/50 HRC

INTENSITY CONDITION	MEDIA SIZE/TYPE	CYCLES TO FAILURE (Nf x 1000)	WEIBULL W	MEAN $\bar{X}$	FRACTURE INITIATION (# OF SPEC. INT.	EXT
BASELINE (UNPEENED)	N/A	27, 35, 40, 41, 50, 51	7	41	0	6
0.0020A	S-70/ CAST STEEL	1375, 1509, 1055, 2033, 644, 1910, 985	267	1359	7	0
0.0040A	S-70/ CAST STEEL	100, 675, 751, 616, 1187, 176, 157, 123	30	473	4	4
0.0060A	S-70/ CAST STEEL	72, 326, 68, 68,44, 71, 62. 97	26	101	0	8
0.0080A	S-70/ CAST STEEL	74, 65, 62, 68, 90, 102, 55, 48	26	71	0	8
0.0100A	S-70/ CAST STEEL	58, 62, 56, 28, 58, 58. 55. 43	17	52	0	8
0.0120A	S-110/ CAST STEEL	57, 19, 57, 34, 80, 52, 52, 50	N/A	50	0	8
0.0140A	S-110/ CAST STEEL	40, 62, 44	N/A	49	0	3

TEST GROUP : FATIGUE LIFE VERSUS INTENSITY (TASK 2)
MATERIAL : 4340 VACUUM ARC REMELT STEEL 48/50 HRC (LOT C-0028)
SPECIMEN SURFACE : GROUND
WORKPIECE SATURATION : 100%
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 195

APPENDIX A

TABLE A-13

FATIGUE RESULTS VS. STRESS, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 7075-T73 ALUMINUM

SPECIMEN STATUS	MAXIMUM STRESS (KSI)	% OF BASELINE STRESS	CYCLES TO FAILURE (Nf x 1000)	MEAN $\overline{X}$	FRACTURE INITIATION (# OF SPEC.)	
PEENED	60	120	46, 39	43	N/A	N/A
CONTROL	60	120	29, 21	25	N/A	N/A
PEENED	57.5	115	64, 94	79	N/A	N/A
CONTROL	57.5	115	34, 35	35	N/A	N/A
PEENED	55	110	309, 212, 268	263	N/A	N/A
CONTROL	55	110	36, 39, 72, 37	46	N/A	N/A
PEENED	52.5	105	718, 514	616	N/A	N/A
CONTROL	52.5	105	241, 158	200	N/A	N/A
PEENED	50	100	2805, 1811, 2093, 1176 1385, 1822, 1096	1741	N/A	N/A
CONTROL	50	100	66, 24, 34, 112, 47	57	N/A	N/A
PEENED	47.5	95	1486 1222	1354	N/A	N/A
CONTROL	47.5	95	450	N/A	N/A	N/A
CONTROL	47	94	61, 209, 398	223	N/A	N/A
PEENED	45	90	3068, 107, 1963	1713	N/A	N/A
CONTROL	45	90	150, 894, 1195	746	N/A	N/A
PEENED	42.5	85	3333	N/A	N/A	N/A
CONTROL	42.5	85	229, 368	299	N/A	N/A
CONTROL	40	80	4608	N/A	N/A	N/A

TEST GROUP : FATIGUE LIFE VERSUS STRESS (TASK 2 - S/N)
MATERIAL : 7075-T73 ALUMINUM 136 HBN (LOT C-0030)
SPECIMEN SURFACE : LATHE TURNED & POLISHED (C)
ALMEN INTENSITY : 0.0020A (OPTIMUM PER TASK 2)
WORKPIECE SATURATION : 100% (OPTIMUM PER TASK 4)
MEDIA SIZE/TYPE : S-70 CAST STEEL
ANGLE OF IMPACT : 90 DEGREES

APPENDIX A

TABLE A-14

FATIGUE RESULTS VS. STRESS, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 4340 AIRMELT STEEL 48/50 HRC

SPECIMEN STATUS	MAXIMUM STRESS (KSI)	% OF BASELINE STRESS	CYCLES TO FAILURE (Nf x 1000)	MEAN X̄	FRACTURE INITIATION (# OF SPEC. INT.	EXT
PEENED	212.5	125	29	N/A	N/A	N/A
CONTROL	212.5	125	16, 17	17	N/A	N/A
PEENED	204	120	40, 50	45	N/A	N/A
CONTROL	204	120	40, 47	44	N/A	N/A
PEENED	195.5	115	45, 103	74	N/A	N/A
CONTROL	195.5	115	21, 1006	514	N/A	N/A
PEENED	187	110	143, 145	144	N/A	N/A
CONTROL	187	110	52, 54	53	N/A	N/A
PEENED	178.5	105	267, 279, 130, 227	226	N/A	N/A
CONTROL	178.5	105	137, 211	174	N/A	N/A
PEENED	170	100	(R/O),(R/O),96, (R/O),291,7784,185	2089	N/A	N/A
CONTROL	170	100	108, 145	127	N/A	N/A
PEENED	161.5	95	6402 (R/O)	N/A	N/A	N/A
CONTROL	161.5	95	294, (R/O)	N/A	N/A	N/A
PEENED	153	90	(R/O) (R/O)	N/A	N/A	N/A
CONTROL	153	90	1010, (R/O)	N/A	N/A	N/A
PEENED	144.5	85	(R/O) (R/O)	N/A	N/A	N/A
CONTROL	144.5	85	(R/O)	N/A	N/A	N/A

TEST GROUP : FATIGUE LIFE VERSUS STRESS (TASK 2 - S/N)
MATERIAL : 4340 AIRMELT STEEL 48/50 HRC (LOT C-0025)
SPECIMEN SURFACE : GROUND & POLISHED
ALMEN INTENSITY : 0.0080A (OPTIMUM PER TASK 2)
WORKPIECE SATURATION : 100% (OPTIMUM PER TASK 4)
MEDIA SIZE/TYPE : S-70 CAST STEEL
ANGLE OF IMPACT : 90 DEGREES

APPENDIX A

TABLE A-15

FATIGUE RESULTS VS. STRESS, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 4340 VACUUM ARC REMELT STEEL 48/50 HRC

SPECIMEN STATUS	MAXIMUM STRESS (KSI)	% OF BASELINE STRESS	CYCLES TO FAILURE (Nf x 1000)	MEAN $\bar{X}$ X	FRACTURE INITIATION (# OF SPEC. INT.	EXT
PEENED	215	110	41, 39, 35	38	N/A	N/A
PEENED	205	105	410, 462, 216, 111	300	N/A	N/A
CONTROL	204	104.5	25	N/A	N/A	N/A
PEENED	195	100	1375, 1509, 1055, 985, 2033, 1910, 664	1362	N/A	N/A
CONTROL	195	100	27, 35, 40, 41, 50, 51	41	N/A	N/A
CONTROL	191	98	1814	N/A	N/A	N/A
CONTROL	187	96	65, 46, 35, (R/O) (R/O)	49	N/A	N/A
PEENED	186	95.5	1895, 1071	1483	N/A	N/A
CONTROL	183.6	94	(R/O)	N/A	N/A	N/A
CONTROL	182.75	93.5	49, 2309	1169	N/A	N/A
PEENED	175	89.5	1269, 5199, 6266, 2543	3819	N/A	N/A
CONTROL	175	89.5	(R/O) 169, (R/O)	N/A	N/A	N/A
CONTROL	170	87	686, 565, 339, (R/O)	530	N/A	N/A
CONTROL	166	85	96, 208, (R/O) 6083, 18	1643	N/A	N/A

TEST GROUP : FATIGUE LIFE VERSUS STRESS (TASK 2 - S/N)
MATERIAL : 4340 VACUUM ARC REMELT STEEL 48/50 HRC
SPECIMEN SURFACE : GROUND
ALMEN INTENSITY : 0.0020A (OPTIMUM PER TASK 2)
WORKPIECE SATURATION : 100% (OPTIMUM PER TASK 4)
MEDIA SIZE/TYPE : S-70 CAST STEEL
ANGLE OF IMPACT : 90 DEGREES

APPENDIX A

TABLE A-16

FATIGUE RESULTS VS. INTENSITY VS. PREPEENING SURFACE CONDITION, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 7075-T6 ALUMINUM

INTENSITY CONDITION	MEDIA SIZE/TYPE	CYCLES TO FAILURE (Nf x 1000)	WEIBULL W	MEAN $\bar{X}$	FRACTURE INITIATION (# OF SPEC. INT.	EXT)
BASELINE (UNPEENED)	N/A	57, 47, 29, 24	N/A	39	0	6
0.0020A	S-70/ CAST STEEL	281, 183, 105, 232, 439, 295	22	256	6	0
0.0040A	S-70/ CAST STEEL	387, 197, 358, 242, 362, 313	68	310	6	0
0.0060A	S-70/ CAST STEEL	285, 242, 265, 146, 302, [illegible]	77	252	2	4
0.0080A	S-70/ CAST STEEL	93, 85, 130, 82, 99, 118	50>	101	0	6

TEST GROUP : FATIGUE LIFE VERSUS INTENSITY (TASK 3)
MATERIAL : 7075-T6 ALUMINUM 143 HBN (LOT C-0002)
SPECIMEN SURFACE : LATHE TURNED
WORKPIECE SATURATION : 100%
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 58

APPENDIX A

TABLE A-17

FATIGUE RESULTS VS. WORKPIECE SATURATION, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION OF TITANIUM 6AL-4V

SPECIMEN STATUS	WORKPIECE SATURATION	CYCLES TO FAILURE (Nf x 1000)	MEAN $\bar{X}$	FRACTURE INITIATION (# OF SPEC.) INT.	EXT
CONTROL	N/A	61, 64, 83, 134, 185, 214, 5711	922	N/A	N/A
PEENED	90%	4753, 4574, 24	3117	N/A	N/A
PEENED	100%	1179, 1471, 2523, 1753, 3754, 1732, 1656	2010	N/A	N/A
PEENED	125%	1648, 586, 415	883	N/A	N/A
PEENED	150%	1067, 188, 217	491	N/A	N/A
PEENED	175%	1380, 1858, 65	1101	N/A	N/A
PEENED	200%	138, 580, 1685	801	N/A	N/A

TEST GROUP : FATIGUE [illegible]E VERSUS WORKPIECE SATURATION (TASK 4)
MATERIAL : 6AL-4V [illegible]NIUM 41/42 HRC (LOT C-0015)
SPECIMEN SURFACE : LATHE T[illegible]D AND POLISHED (C)
ALMEN INTENSITY : 0.0020A ([illegible]TIMUM PER TASK 2)
MEDIA SIZE/TYPE : MIL-13 GLASS BEAD
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 140

APPENDIX A

TABLE A-18

FATIGUE RESULTS VERSUS WORKPIECE SATURATION, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION OF 2024-T4 ALUMINUM

SPECIMEN STATUS	WORKPIECE SATURATION	CYCLES TO FAILURE (Nf x 1000)	MEAN $\bar{X}$	FRACTURE INITIATION (# OF SPEC.) INT.	EXT
CONTROL	N/A	184, 162, 141, 138, 186, 129	157	0	6
PEENED	90%	125, 133, 37	98	3	0
PEENED	100%	1235, 947, 1110, 293	896	5	N/A
PEENED	200%	496, 1009, 1212	906	3	0
PEENED	250%	929, 992, 1256, 120, 355, 188, 73, 95, 82	454	3	N/A
PEENED	300%	316, 1205, 165, 59, 46, 60	309	6	0
PEENED	350%	58, 130, 94	94	N/A	N/A
PEENED	400%	79, 103, 138	107	3	0

TEST GROUP : FATIGUE LIFE VERSUS WORKPIECE SATURATION (TASK 4)
MATERIAL : 2024-T4 ALUMINUM 100/119 HBN (LOT C-0001)
SPECIMEN SURFACE : LATHE TURNED & POLISHED (C)
ALMEN INTENSITY : 0.0010A (OPTIMUM PER TASK 2)
MEDIA SIZE/TYPE : MIL-13 GLASS BEAD
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 47

APPENDIX A

TABLE A-19

FATIGUE RESULTS VS. WORKPIECE SATURATION, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION OF 6061-T6 ALUMINUM

SPECIMEN STATUS	WORKPIECE SATURATION	CYCLES TO FAILURE (Nf x 1000)	MEAN $\bar{X}$	FRACTURE INTITATION (# OF SPEC.) INT.	EXT
CONTROL	N/A	64, 447, 224, 158, 130 412	239	N/A	N/A
PEENED	80%	90, 468, 440	333	N/A	N/A
PEENED	90%	983, 939, 1021, 399, 374, 719	739	N/A	N/A
PEENED	100%	490, 648, 940, 1054, 931	813	N/A	N/A
PEENED	200%	560, 109, 239	303	N/A	N/A
PEENED	250%	131, 213, 150, 72, 57, 644	211	N/A	N/A
PEENED	300%	180, 937, 68	395	N/A	N/A
PEENED	350%	136, 146, 361	214	N/A	N/A

TEST GROUP : FATIGUE LIFE VERSUS WORKPIECE SATURATION (TASK 4)
MATERIAL : 6061-T6 ALUMINUM 93/100 HBN (LOT C-0003)
SPECIMEN SURFACE : LATHE TURNED & POLISHED (C)
ALMEN INTENSITY : 0.0010A (OPTIMUM PER TASK 2)
MEDIA SIZE/TYPE : MIL-13 GLASS BEAD
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 40

APPENDIX A

TABLE A-20

FATIGUE RESULTS VS. WORKPIECE SATURATION, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION OF 7076-T6 ALUMINUM

SPECIMEN STATUS	WORKPIECE SATURATION	CYCLES TO FAILURE (Nf x 1000)	WEIBULL W	MEAN $\overline{X}$	FRACTURE INITITATION (# OF SPEC.) INT.	EXT.
CONTROL	N/A	84, 99, 82, 217, 197, 93	N/A	129	N/A	N/A
PEENED	80%	229, 297, 392	N/A	306	N/A	N/A
PEENED	90%	241, 238, 391	N/A	290	N/A	N/A
PEENED	100%	298, 275, 360, 323, 357, 383	110	333	N/A	N/A
PEENED	150%	338, 331, 319, 308, 284, 373, 276	196	318	N/A	N/A
PEENED	200%	295. 344, 337, 348, 285, 234	129	307	N/A	N/A
PEENED	250%	223, 220, 392	N/A	278	N/A	N/A

TEST GROUP : FATIGUE LIFE VERSUS WORKPIECE SATURATION (TASK 4)
MATERIAL : 7075-T6 ALUMINUM 143 HBN (LOT C-0002)
SPECIMEN SURFACE : LATHE TURNED & POLISHED (C)
ALMEN INTENSITY : 0.0010A (OPTIMUM PER TASK 2)
MEDIA SIZE/TYPE : MIL-13 GLASS BEAD
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 58

APPENDIX A

TABLE A-21

FATIGUE RESULTS VERSUS WORKPIECE SATURATION, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION OF 7075-T73 ALUMINUM

SPECIMEN STATUS	WORKPIECE SATURATION	CYCLES TO FAILURE (Nf x 1000)	MEAN $\bar{X}$	FRACTURE INITIATION (# OF SPEC. INT.	EXT
CONTROL	N/A	66, 24, 34, 112, 4, (R/O)	57	N/A	5
PEENED	100%	2805, 1811, 2093, 1176, 1385, 1822, 1096	1741	7	0
PEENED	200%	1712, 1784	1748	N/A	N/A
PEENED	400%	1597, 1387, 2022, 2841	1962	N/A	N/A
PEENED	600%	2649, 2067, 2590, 84	1848	N/A	N/A
PEENED	800%	1005, 2131, 1398	1511	N/A	N/A

TEST GROUP : FATIGUE LIFE VERSUS WORKPIECE SATURATION (TASK 4)
MATERIAL : 7075-T73 ALUMINUM 136 HBN (LOT C-0030)
SPECIMEN SURFACE : LATHE TURNED & POLISHED (C)
ALMEN INTENSITY : 0.0020A (OPTIMUM PER GROUP B)
MEDIA SIZE/TYPE : S-70 CAST STEEL
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 50

APPENDIX A

TABLE A-22

FATIGUE RESULTS VERSUS WORKPIECE SATURATION, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION OF 4340 AIRMELT STEEL 40/42 HRC

SPECIMEN STATUS	WORKPIECE SATURATION	CYCLES TO FAILURE (Nf x 1000)	MEAN $\overline{X}$	FRACTURE INITIATION (# OF SPEC.) INT.	EXT
CONTROL	N/A	241, 143, 93	159	0	3
PEENED	100%	(R/O) (R/O) (R/O) (R/O) (R/O) (R/O)	N/A	N/A	N/A
PEENED	150%	(R/O) (R/O) (R/O)	N/A	N/A	N/A
PEENED	200%	(R/O)	N/A	N/A	N/A
PEENED	250%	(R/O) (R/O)	N/A	N/A	N/A
PEENED	300%	(R/O) (R/O)	N/A	N/A	N/A
PEENED	350%	(R/O) (R/O)	N/A	N/A	N/A
PEENED	400%	989, 635	812	N/A	N/A

TEST GROUP : FATIGUE LIFE VS. WORKPIECE SATURATION (TASK 4)
MATERIAL : 4340 AIRMELT STEEL 40/42 HRC (LOT C-0020)
SPECIMEN SURFACE : GROUND & POLISHED (L)
ALMEN INTENSITY : 0.0040A (OPTIMUM PER TASK 2)
MEDIA SIZE/TYPE : S-70 CAST STEEL
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 155

APPENDIX A

TABLE A-23

FATIGUE RESULTS VS. WORKPIECE SATURATION, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION OF 4340 AIRMELT STEEL 48/50 HRC

SPECIMEN STATUS	WORKPIECE SATURATION	CYCLES TO FAILURE (Nf x 1000)	MEAN $\bar{X}$	FRACTURE INITIATION (# OF SPEC. INT.	EXT
CONTROL	N/A	61, 97, 46, 48, 70, 93, 106	74	0	7
PEENED	100%	495, 558, (R/O) 1011, 242, 245, 934, 495, 225, 478, 1037, 685, 311, 791, 719, 795, 1113, 1019, 758	662	7	6
PEENED	120%	2289, 549, 182, 633, 497	830	N/A	N/A
PEENED	130%	1480, 566, 724, 212, 397, 135	586	N/A	N/A
PEENED	140%	334, 1189, 323, 482,335	533	N/A	N/A
PEENED	150%	159, 348, 303, 727, 549	417	N/A	N/A
PEENED	180%	687, 1024, 1023	911	N/A	N/A
PEENED	200%	700, 118, 139, 178, 341	295	N/A	N/A
PEENED	250%	302, 155	229	N/A	N/A
PEENED	400%	235, 187	211	N/A	N/A

TEST GROUP : FATIGUE LIFE VERSUS WORKPIECE SATURATION (TASK 4)
MATERIAL : 4340 AIRMELT STEEL 48/50 HRC (LOT C-0021)
SPECIMEN SURFACE : GROUND AND POLISHED (L)
ALMEN INTENSITY : 0.0080A
MEDIA SIZE/TYPE : S-70 CAST STEEL
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 170

APPENDIX A

TABLE A-24

FATIGUE RESULTS VS. WORKPIECE SATURATION, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION OF 4340 VACUUM ARC REMELT 48/50 HRC

SPECIMEN STATUS	WORKPIECE SATURATION	CYCLES TO FAILURE (Nf x 1000)	MEAN $\bar{X}$	FRACTURE INITIATION (# OF SPEC.) INT.	EXT.
CONTROL	N/A	27, 35, 40, 41, 50, 51	41	N/A	4
PEENED	100%	1375, 1509, 1055, 664, 2033, 1910, 985	1362	7	0
PEENED	200%	1139, 641, 1399, 542	930	4	0
PEENED	400%	2042, 1056, 683, 1609	1348	4	0
PEENED	600%	914, 897, 219, 156	547	4	0

TEST GROUP : FATIGUE LIFE VERSUS WORKPIECE SATURATION (TASK 4)
MATERIAL : 4340 VACUUM ARC REMELT STEEL 48/50 HRC (LOT C-0028
SPECIMEN SURFACE : GROUND
ALMEN INTENSITY : 0.0020A (OPTIMUM PER TASK 2)
MEDIA SIZE/TYPE : S-70 CAST STEEL
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 195

APPENDIX A

TABLE A-25

FATIGUE RESULTS VERSUS IMPACT ANGLE, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 7075-T73 ALUMINUM

SPECIMEN STATUS	ANGLE OF IMPACT	CYCLES TO FAILURE (Nf x 1000)	WEIBULL W	MEAN $\bar{X}$	FRACTURE INITIATION (# OF SPEC.) INT.	EXT
CONTROL	N/A	66, 24, 34, 112, 47	4	57	0	5
PEENED	90 DEGREE	2805, 1811, 2093, 1822, 1096, 1176, 1385	291	1741	7	0
PEENED	60 DEGREE	2325, 961, 1820, 1437, 1618, 1437	438	1600	6	0
PEENED	45 DEGREE	1029, 2582, 2438, 1988, 265, 93	.4(EST)	1399	6	0

TEST GROUP : FATIGUE LIFE VERSUS ANGLE OF IMPACT (TASK 5)
MATERIAL : 7075-T73 ALUMINUM 136 BHN (LOT C-0030)
SPECIMEN SURFACE : LATHE TURNED AND POLISHED (C)
ALMEN INTENSITY : 0.0020A (OPTIMUM PER TASK 2)
WORKPIECE SATURATION : 100% (OPTIMUM PER TASK 4)
MEDIA SIZE/TYPE : S-70 CAST STEEL
MAXIMUM STRESS (KSI) : 50

APPENDIX A

TABLE A-26

FATIGUE RESULTS VS. IMPACT ANGLE, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 4340 VACUUM ARC REMELT STEEL 48/50 HRC

SPECIMEN STATUS	ANGLE OF IMPACT	CYCLES TO FAILURE (Nf x 1000)	WEIBULL W	MEAN $\bar{X}$	FRACTURE INITIATION (# OF SPEC.) INT.	EXT
CONTROL	N/A	27, 35, 40, 41, 50, 51	7	41	0	6
PEENED	90 DEGREE	1375, 1509, 1055, 2033, 1910, 985, 664	267	1362	7	0
PEENED	60 DEGREE	2028, 1328, 502, 423, 341, 317, 1444, 918, 1920	6	1025	8	N/A
PEENED	45 DEGREE	954, 750, 1534, 875, 1766, 1077, 1207 1602, 434	128	1133	9	0

TEST GROUP : FATIGUE LIFE VERSUS ANGLE OF IMPACT (TASK 5)
MATERIAL : 4340 VACUUM ARC REMELT STEEL 48/50 HRC (LOT C-0028, C-0031)
SPECIMEN SURFACE : GROUND
ALMEN INTENSITY : 0.0020A (OPTIMUM PER TASK 2)
WORKPIECE SATURATION : 100% (OPTIMUM PER TASK 4)
MEDIA SIZE/TYPE : S-70 CAST STEEL
MAXIMUM STRESS (KSI) : 195

APPENDIX A

TABLE A-27

FATIGUE RESULTS VS. BROKEN PARTICLE CONTENT, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION OF 7075-T73 ALUMINUM

SPECIMEN STATUS	% OF GRIT BY WEIGHT	CYCLES TO FAILURE (Nf x 1000)	WEIBULL W	MEAN $\bar{X}$	FRACTURE INITIATION (# OF SPEC. INT.	EXT
CONTROL	2 OR LESS	66, 24, 34, 47, 112	4	57	0	5
PEENED	2 OR LESS	2805, 1811, 2093, 1096, 1822, 1385, 1176	291	1741	7	0
PEENED	25	1991, 1018, 2137, 938, 1053, 1661, 1407	266	1458	7	0
PEENED	50	276, 109, 770, 1190, 1341, 804, 587	4	725	7	0
PEENED	75	314, 590, 771, 386, 307, 1047, 795	25	601	7	0

TEST GROUP : FATIGUE LIFE VERSUS BROKEN PARTICLE CONTENT (TASK 6)
MATERIAL : 7075-T73 ALUMINUM 136 HBN (LOT C-0030)
SPECIMEN SURFACE : LATHE TURNED AND POLISHED (C)
ALMEN INTENSITY : 0.0020A (OPTIMUM PER TASK 2)
WORKPIECE SATURATION : 100% (OPTIMUM PER TASK 4)
MEDIA (SHOT) SIZE/TYPE : S-70 CAST STEEL
MEDIA (GRIT) SIZE/TYPE : LG-80 CAST STEEL
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 50

APPENDIX A

TABLE A-28

FATIGUE RESULTS VS. BROKEN PARTICLE CONTENT, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION OF 4340 VACUUM ARC REMELT STEEL 48/50 HRC

SPECIMEN STATUS	% OF GRIT BY WEIGHT	CYCLES TO FAILURE (Nf x 1000)	WEIBULL W	MEAN $\overline{X}$	FRACTURE INITIATION (# OF SPEC. INT.	EXT
CONTROL	2 OR LESS	27, 35, 40, 41, 50, 51	7	41	0	4
PEENED	2 OR LESS	1375, 1509, 1055, 2033, 1910, 985,664	267	1362	7	0
PEENED	25	896, 791, 319, 494, 796, 1605, 1228,859	85	874	8	0
PEENED	50	1121, 211, 1034, 1138,490, 343, 877, 1264	18	810	8	0
PEENED	75	1105, 907, 51, 290, 213, 199, 422, 805	.6	499	4	4

TEST GROUP : FATIGUE LIFE VERSUS BROKEN PARTICLE CONTENT (TASK 6)
MATERIAL : 4340 VACUUM ARC REMELT STEEL 48/50 HRC (LOT C-0031)
SPECIMEN SURFACE : GROUND
ALMEN INTENSITY : 0.0020A (OPTIMUM PER TASK 2)
WORKPIECE SATURATION : 100% (OPTIMUM PER TASK 4)
MEDIA (SHOT) SIZE/TYPE : S-70 CAST STEEL
MEDIA (GRIT) SIZE/TYPE : LG-80 CAST STEEL
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 195

APPENDIX A

TABLE A-29

FATIGUE LIFE VS. INTENSITY VS. MEDIA TYPE, PEENING PARAMETERS AND FRACTURE SITE DETERMINATION FOR 7075-T73 ALUMINUM

INTENSITY CONDITION	MEDIA SIZE/TYPE	CYCLES TO FAILURE (Nf x 1000)	MEAN $\bar{X}$	FRACTURE INITIATION (% OF SPEC.) INT.	EXT
BASELINE (UNPEENED)	N/A	40, 157, 53, 48, 47, 50, (R/O), 1830, 1576, 101, 682	458	N/A	N/A
0.0010A	MIL-13/ GLASS BEAD	2160, 1664, 1471	1765	N/A	N/A
0.0010A	S-70/ CAST STEEL	2256, 1223, 1471	1650	N/A	N/A
0.0020A	S-70/ CAST STEEL	2046, 1041, 2805, 1811, 2093, 1176, 1385, 1822, 1096	1697	N/A	N/A
0.0030A	MIL-11/ GLASS BEAD	1102, 1386, 1875	1454	N/A	N/A
0.0030A	S-70/ CAST STEEL	1045, 1397, 1244	1229	N/A	N/A
0.0050A	MIL-8/ GLASS BEAD	993, 211	602	N/A	N/A
0.0060A	S-70/ CAST STEEL	260, 270, 163, 1262	489	N/A	N/A

TEST GROUP : FATIGUE LIFE VERSUS INTENSITY (TASK 7)
MATERIAL : 7075-T73 ALUMINUM 158 HBN (LOT C-0017)
SPECIMEN SURFACE : LATHE TURNED AND POLISHED (C)
WORKPIECE SATURATION : 100%
ANGLE OF IMPACT : 90 DEGREES
MAXIMUM STRESS (KSI) : 50